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Design and Development of a Lightweight Caravan Chassis and Suspension System

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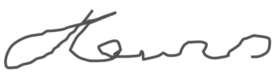

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Abstract

Over the past five years caravan manufacturers have dramatically changed their approach to the design, construction and manufacture of their products. What was a very traditional cottage industry has now become a hi-tech and extremely competitive sector driven by lean manufacturing processes. This investment into new technologies has led to the development of a product that now offers improved build quality, enhanced structural rigidity, reduced water ingress and improved thermal insulation.

The majority of investment over this period has been into the body shell of the caravan and despite the advances in the development of the sides and roof panels, the caravan floor, chassis and suspension are still constructed using materials and components that have altered little in the last thirty years. It is believed that the current chassis and suspension system is inadequate in terms of isolation from road imperfections, structural performance, weight, weather proofing and cost. It was the intention of this project to investigate how this substructure could be redesigned to match the performance characteristics of the rest of the caravan.

This thesis outlines the investigation and product development process and proposes a new design for a lightweight caravan chassis and suspension system that provides improved chassis isolation from the road in a package that is 150kg lighter, of comparable stiffness and manufacturing cost.

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1 : Project Introduction

1.1 The Caravan Market

Demand for high value leisure items has been recovering since September 2009, after collapsing for almost two years previously [1]. It has been hypothesised that the effect of the 2008/9 recession in the UK has led to an increasing fraction of the UK population to holiday closer to home rather than travelling abroad [2]. The UK caravan market has therefore seen promising growth and there are now over 30,000 units being sold each year. Moreover, there are around 500,000 caravans in use throughout the UK and last year over one million people decided to holiday in a caravan, equating to nearly a fifth of all UK 'holiday days'. The UK *Caravan Club* alone has over 800,000 members. It is estimated that the expenditure on new and used caravans and caravan holidays is well over £3billion per year with this figure set to significantly increase up to 2013 [3].

There are currently five major UK based caravan manufacturers who have the following market share:

- Bailey (35%)
- Swift Group (33%)
- Lunar (12%)
- Coachman (8%)
- Elddis (12%)

The majority of caravans manufactured in the UK are sold to UK based customers but this is predicted to change in the future with the introduction of new European law. One manufacturer, Bailey Caravans, has begun to export to Australia and is investigating other foreign markets.

Figure 1-1: Bailey Unicorn Valencia

1.2 Introduction to the Project

1.2.1 Current Chassis and Suspension System

The current caravan chassis and suspension system is common to over 80% of all UK caravan manufacturers and is supplied from one manufacturer based in Germany (Alko). The design follows a standard form that has changed little in over 30 years and is common to many other applications besides caravans. A major consequence of the current set-up is that the caravan floor design has also seen little development over the years, as it is integral to the design of the chassis. The floor is manufactured from timber, plywood and Styrofoam (polystyrene) and consequently does not share the same properties as the rest of the body panels that are now manufactured from aluminium, expanded polystyrene and glass reinforced plastic [4]. Moreover the availability of new composite materials, improved insulation and the demand for lighter vehicles makes the requirement for a new and improved chassis design critical. The caravan suspension system is also predominately supplied by Alko and is ubiquitous throughout the market. As discussed later in this report, the suspension system is overly simplistic and is not optimised for achieving good, or even acceptable, handling and ride characteristics. Bailey Caravans, in particular, also want to reduce their reliance on a monopoly supplier and currently see this dependence as a barrier to further improving their product.

1.2.2 Project Aims and Objectives Summary

The overall aim of this project was to design and develop an integrated chassis, floor and suspension system that, for reasons stated above, improves the caravan stiffness, reduces the impact of road defects on the caravan structure, improves the weather proofing of the system and reduces the total towed weight of the caravan.

The first stage of the project was to investigate the performance of the current state-of-the-art caravan design with specific focus on the chassis and suspension system. The investigation comprised of detailed structural analysis of the present, industry standard, chassis system through both simulated models and real-life track based testing. The suspension performance was investigated through laboratory based tests, in-house experimentation and road tests.

Following this investigation the design of the sub-structure was reviewed and an alternative caravan chassis and suspension system were developed. The intention was to design and develop an alternative system that was significantly lighter, as equally robust and cost effective as the incumbent design. It was specified that an overall weight saving of 50kg (or 12% of the chassis weight) should be achieved.

The other key objective of the project was to ensure that the final design could be easily adapted into a mass-produced system, capable of matching the current demand for chassis and suspension systems based on Bailey Caravans' current manufacturing figures, approximately 8,000 caravans per annum.

1.3 Caravan Construction Overview

1.3.1 Coach Construction

Traditional 'coach built' caravans Figure 1-2, are constructed from the inside-out where a wooden frame is filled with insulation then faced with either aluminium, plastic or ply wood [5]. This method of construction results in a strong but heavy structure that can suffer from water ingress causing the wooden frame to rot and fail. This design is almost obsolete within the caravan industry apart from some specialist bespoke manufacturers.

Figure 1-2: Traditional Coach Built Caravan [5]

1.3.2 Sandwich Built Caravans

The majority of modern day caravans are typically constructed from nine separate panels each made up of the same laminated sections. Both the inner and outer skins are bonded to a core of insulating foam (usually polystyrene) and wood, to form a light and rigid structure. Rather than building a frame, in these caravans the strength of the bodywork lies within the bonded sandwich construction of the walls, floor and roof. Wooden inserts in the sandwich walls are fixed to the floor, and as the walls are sealed, there is no need to provide any further treatment. While sandwich construction offers the benefits of lighter weight and greater structural rigidity, the main problem relates to the number of joints involved. With typically nine panels forming the structure, it is important to ensure all the joints are sealed. Occasionally however there are problems with the sealant methods, resulting in water entering the structure. If the bonding insulation is the open-cell type then the system acts like a sponge, absorbing and spreading the liquid. The more expensive method (closed-cell foam) cannot absorb the water - resulting in a localised problem. Yet despite these improved construction methods the problem remains: the more joints on a structure, the more areas there are that require sealing to battle the elements [5].

1.3.3 Modern Caravans

The latest construction system adopted by Bailey Caravans [4] replaces all of the wooden elements in the sandwich construction with a high-density extruded polystyrene material that eliminates the chance of internal rotting. The method also dramatically reduces the number of water ingress points through the use of five panels joined through an aluminium extrusion clamping system. The construction also significantly improves the structural rigidity of the caravan as it is now akin to a monocoque shell, distributing loads more evenly throughout the structure [4]. More detail on this system can be found in Appendix I.

1.4 Caravan Chassis Floor and Suspension

1.4.1 The Caravan Chassis

At present the majority of caravans use the Alko Vario II system, Figure 1-3. The system comprises of two sets of steel member sections (a), the hitch system (b), four stays (c), the axle and suspension assembly (d) and the spare tyre frame (e). The steel members are bolted together to form the two main struts of the chassis that meet at the hitch point. The length of the chassis can be adjusted through the use of multiple fixing locations. The chassis is supplied by Alko in kit form and is assembled on site.

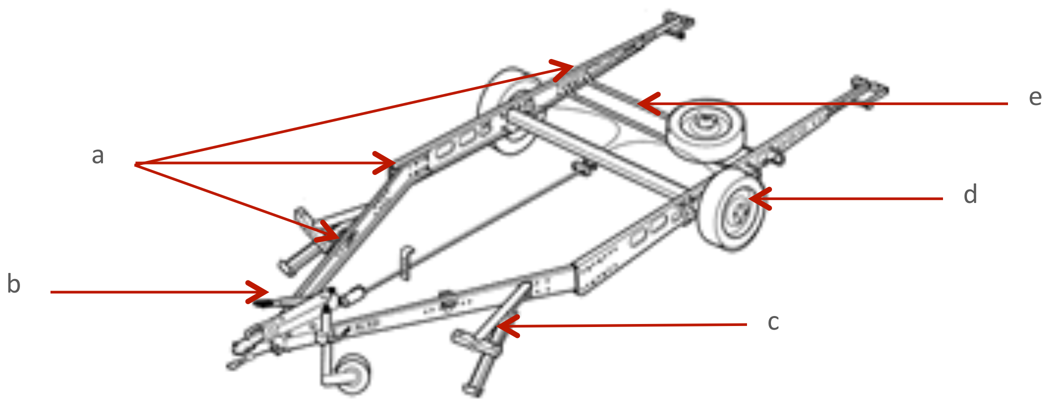


Figure 1-3: Alko Chassis [6]

The chassis is heavily reliant on the addition of the floor to increase its structural rigidity to reach an acceptable stiffness level as discussed later in this study. Moreover, the chassis can fail when subjected to extreme accelerated life road tests such as the D85C carried out on a test track, [7] Appendix II. Figure 1-4 shows the fracture of the chassis near to the axle mount and the failure of interior furniture located over the wheel. The axle is the most heavily loaded part of the chassis and this area of the floor is subjected to the greatest amount of vibration from the road surface.

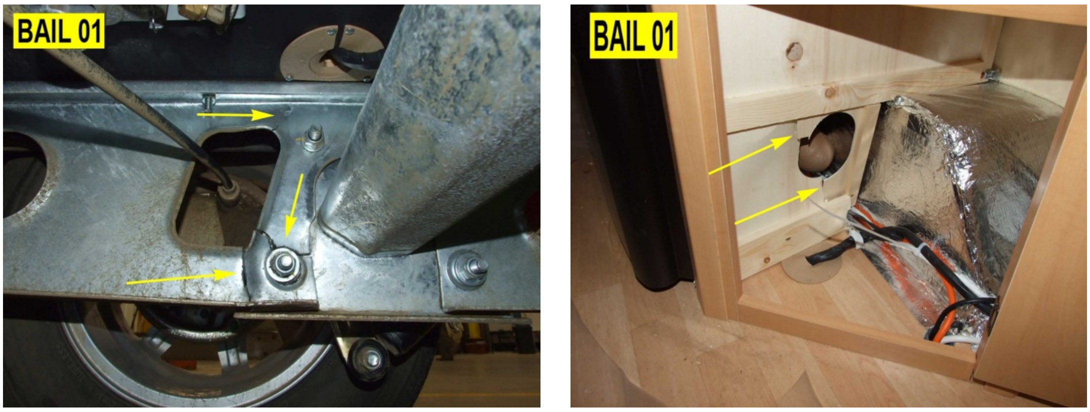


FIGURE 1-4: DAMAGE CAUSED DURING CARAVAN ACCELERATED LIFE TESTS

1.4.2 CARAVAN SUSPENSION

The current suspension system consists of three rubber circular extrusions, contained within a triangular axle case that spans the width of the caravan. As the wheel encounters a bump or pothole an inner triangular shaft rotates inside the outer triangular tube array, imparting a shear and compression load on to the rubber extrusions that absorb the kinetic energy through the hysteresis and stiffness of the rubber, Figure 1-5. The trailing arm of the system is connected to a shock absorber or damper that is designed to control the bump and rebound rates. Suspension systems are a legal requirement of vehicles of this gross weight and are claimed to improve the road holding and cornering performance and minimise shock transmission to the chassis and bodywork. A major advantage of this system is that it requires little or no maintenance leading to a long service life. It also does not require a three-dimensional chassis structure to support the suspension components.

FIGURE 1-5: CARAVAN SUSPENSION SYSTEM [6]

Previous research [8] suggests that the addition of the shock absorber does little to enhance the damping performance of the suspension system. Moreover, it has been shown that the majority of the vibration isolation is achieved through the tyre wall rather than the rubber suspension in the axle [9]. In extreme road conditions the poor suspension performance leads to failure of the chassis and vibrational transmission to the interior of the caravan, Figure 1-4. The compliance of the rubber in the suspension system only provides significant attenuation when the caravan is fully loaded [9] although there is a danger that tyre damage may occur.

1.4.3 CARAVAN FLOOR

The current floor is of traditional construction and is comprised of a Styrofoam core with wooden battens sandwiched between layers of heat-treated plywood, Figure 1-6. The wooden battens are stapled to form a framework and the ply is bonded to the Styrofoam using polyurethane adhesive. The floor is placed in a press to ensure reliable adhesion. Once the adhesive has cured, the floor is then bolted directly to the chassis assembly (black ply facing the road). The caravan services are then secured to the underside of the floor, Figure 1-7. The mating of the chassis to the floor creates a reasonably stiff structure that is able to withstand the majority of suspension loads.

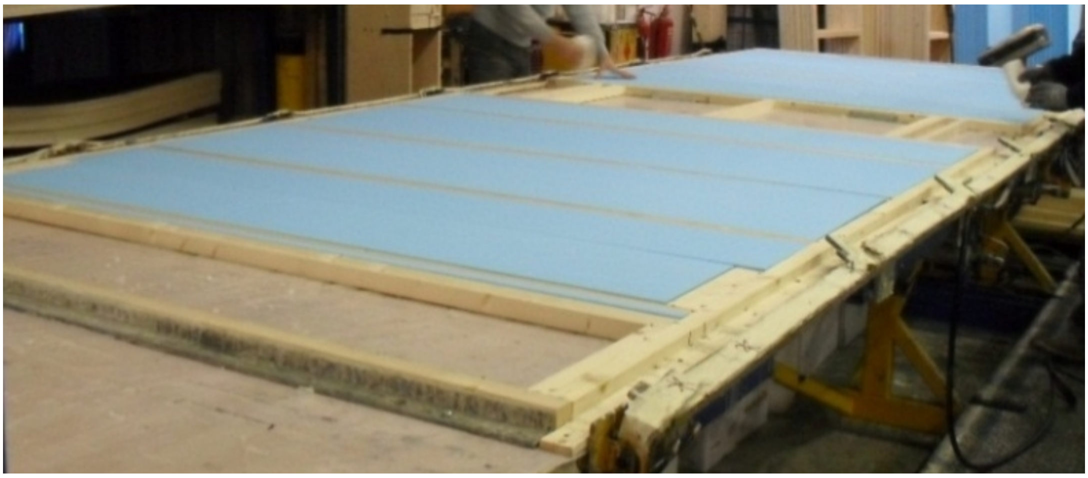


FIGURE 1-6: CARAVAN FLOOR CONSTRUCTION

FIGURE 1-7: CARAVAN FLOOR ASSEMBLY

At present all of the four body shell panels (sides and roof) have no wood in their construction. This mitigates the chance of rot should water penetrate the skin. It is now becoming more common for customers to complain about the deterioration of a caravan floor due to water ingress and it is believed that the design can be improved to remove the wood content.

It is proposed that an integrated floor, chassis and suspension design will not only reduce the overall mass of the caravan, leading to improved fuel consumption of the tow vehicle, but will also increase its stiffness and improve its weather proofing capabilities.

1.5 Chassis, Floor and Suspension Systems in Other Applications

Suspension, chassis and floor designs are common in a wide range of industries and their design and configuration vary greatly from one application to the next. The following section provides an overview of suspension, chassis and floor systems that are used primarily throughout the automotive and aerospace industries.

1.5.1 Suspension Systems

1.5.1.1 Torsion Bar

A torsion bar suspension, also known as a torsion spring suspension is a general term for any vehicle suspension that uses a torsion bar as its main weight bearing spring. One end of a long metal bar is attached firmly to the vehicle chassis; the opposite end terminates in a lever, mounted perpendicular to the bar that is attached to a suspension arm, spindle or the axle. Vertical motion of the wheel causes the bar to twist around its axis and is resisted by the bar's torsional resistance. The effective spring rate of the bar is determined by its length, diameter and material. [10] [11]

Advantages

- *Adjustability of ride height*
- *Unobtrusive compared to coil springs*
- *Cheap to design and manufacture*

Disadvantages

- *Heavy*
- *Inferior ride and handling characteristics*
- *Difficult to control non-linear spring rates*

1.5.1.2 Torsion Beam

A torsion beam suspension is a vehicle suspension similar to a trailing arm suspension but uses a beam to connect both trailing arms. In contrast to a torsion bar suspension, the main weight bearing springs are usually coil springs, either mounted over the shock absorbers or independently from them. Removing anti-roll bars, the central torsion beam allows for a degree of ‘independence’ of each wheel on the axle. [10] [11]

Advantages

- *Cheap to design and manufacture*
- *Compact with minimal intrusion to body*

Disadvantages

- *Heavy*
- *Inferior ride and handling characteristics*

1.5.1.3 Leaf Springs

Leaf springs take the form of a slender arc-shaped length of spring steel of rectangular cross-section. The centre of the arc provides location for the axle, while tie holes are provided at either end for attaching to the vehicle body. For very heavy vehicles, a leaf spring can be made from several leaves stacked on top of each other in several layers, often with progressively shorter leaves. Leaf springs can provide some lateral and longitudinal location, a degree of damping as well as a compliant spring in the vertical axis. While the interleaf friction provides a damping action, it is not well controlled and can result in stiction which is undesirable. For this reason manufacturers have experimented with mono-leaf springs and composite leaf springs. [10] [11]

Advantages

- *Cheap to design and manufacture*
- *Perform well with very heavy loads on rear wheel drive vehicles*

Disadvantages

- *Very heavy, bulky and intrusive*
- *Not easily controlled*

1.5.1.4 MacPherson Strut

This is currently the most widely used front suspension system in cars of European origin. The system comprises of a strut-type spring and shock absorber combination, which pivots on a ball joint on the single, lower arm. At the top end there is a needle roller bearing on some more sophisticated systems. The strut itself is the load-bearing member in this assembly, with the spring and shock absorber becoming active during a bump. [10] [11]

Advantages

- *Good ride quality and road holding characteristics*
- *The suspension is compact and allows for small overall chassis dimensions.*
- *Good clearance for axles*

Disadvantages

- *Has to be designed for a standard tyre width as it is difficult to increase once fitted. Increased tyre width leads to a larger scrub radius and increased wear.*
- *Lack of camber gain causing the chassis to roll on the suspension when a bump is induced.*

1.5.1.5 Trailing Arm

The trailing arm system comprises of an A shaped suspension arm that joins at the front to the chassis, allowing the rear to swing up and down. Pairs of these become twin-trailing-arm systems and work on exactly the same principle as the double wishbones in the systems described below. The difference is that instead of the arms being positioned laterally from the side of the chassis, they are positioned longitudinally such that the arms are 'trailing'. [10] [11]

Advantages

- *Good ride quality for early suspension systems*
- *Minimises scrub angle during suspension travel.*
- *Can be compact and minimal components*

Disadvantages.

- *A low roll centre which produces large body roll during manoeuvres*
- *Large structure required to support the trailing arms and large arms to support lateral and longitudinal loads.*

1.5.1.6 Rover MacPherson Strut Derivative

This suspension is derived from a normal MacPherson strut but with an added bell crank. This allows the suspension unit to sit horizontally along the outside of the engine bay rather than protruding into it and taking up space. The bell crank transfers the upward forces from the suspension into rearward forces for the spring / shock combination to dampen. [10] [11]

Advantages

- *Good ride quality and road holding characteristics*
- *The suspension is very compact and allows for smaller overall chassis dimensions.*
- *Good clearance for axles*

Disadvantages

- *Has to be designed for a standard tyre width as it is difficult to increase once fitted. Increased tyre width leads to a larger scrub radius and increased wear.*
- *Lack of camber gain causing the chassis to roll on the suspension when a bump is induced.*
- *More moving parts than original design*

1.5.1.7 Double Wishbone

This is a type of double-A or double wishbone suspension. The wheel spindles are supported by an upper and lower 'A' shaped arm. In this type, the lower arm carries most of the load. It is a parallelogram system that allows the spindles to travel vertically up and down. This movement imparts a slight scrub motion caused by the arc that the wishbones describe around their pivot points. Unless the links are infinitely long the scrub motion is always present. The double wishbone system can be configured with equal or un-equal length arms (on un equal systems the top arm is shorter). Un-equal arm systems are commonly used where good cornering characteristics are required and where tyre wear is not as important e.g. racing. [10] [11]

Advantages

- *Excellent handling characteristics and ride quality.*
- *Double connection to the chassis prevent deflection during cornering*
- *Efficient use of space*

Disadvantages

- *Expensive to design and manufacture*

1.5.1.8 Multi-Link

This is the latest incarnation of the double wishbone system described above. The basic principle is the same, but instead of solid upper and lower wishbones, each 'arm' of the wishbone is a separate item. These are joined at the top and bottom of the spindle thus forming the wishbone shape. As the spindle turns for steering, it alters the geometry of the suspension. They have complex pivot systems designed to allow this to happen.

Car manufacturers claim that this system gives even better road-holding properties, because all the various joints make the suspension almost infinitely adjustable. There are a lot of variations on this theme, with huge differences in the numbers and complexities of joints, numbers of arms, positioning of the parts etc. but they are all fundamentally the same. [10] [11]

Advantages

- *High performance handling characteristics and superior ride quality.*

Disadvantages

- *Expensive to design and manufacture*

Table 1-1 provides an initial relative comparison of the various suspension systems available on today's market. The characteristics are weighted with regard to the main aims of the project. This gives an early indication into which suspensions systems may or may not be appropriate for use on a caravan.

Suspension	***Ride & Handling***	***Size (Bulk)***	***Weight***	***Cost***	***Maintainability***	***Total***
Weighting	*0.2*	*0.2*	*0.3*	*0.2*	*0.1*	*/5*
Torsional Bar	*1*	*3*	*1*	*5*	*4*	*2.5*
Torsional Beam	*3*	*3*	*2*	*3*	*3*	*2.7*
Leaf Spring	*1*	*3*	*2*	*4*	*2*	*2.4*
Trailing Arm	*3*	*3*	*3*	*3*	*3*	*3*
MacPherson Strut	*4*	*2*	*3*	*2*	*2*	*2.7*
Rover P6	*4*	*3*	*3*	*2*	*2*	*2.9*
Double Wishbone	*5*	*2*	*3*	*1*	*2*	*2.7*
Multi-Link	*5*	*2*	*3*	*1*	*2*	*2.7*

Table 1-1: Suspension Review

1.5.2 Chassis Systems

There are many automotive chassis design options. The following section provides a broad summary of the different varieties. Whilst there are many overlaps, it is important to note that the approach to the design of a car chassis is different to that of a trailer or caravan chassis. Car chassis engineers have to consider elements such as drive train, engine mounting, passenger safety as well as ride stability and load.

1.5.2.1 Body - on- Frame

The vehicle body is mounted on a rigid frame that supports the drivetrain. This method was used on early car production and in the USA where frequent changes in car design made it necessary to use a ladder frame rather than monocoque. This made it possible to change the design without having to change the chassis, allowing frequent changes and improvements to the car's bodywork and interior while leaving the chassis and driveline unchanged, and thus keeping cost down and design time short. This method is very similar to the current caravan manufacturing process.

Advantages

- *Easier to design, build and modify*
- *More suited for heavy-duty usage such as towing and off-roading; can be more durable.*
- *Easier to repair after accidents.*
- *In an environment where roads are salted, it will not rust through as quickly.*
- *Could allow a manufacturer to easily sub-contract portions of work.*

Disadvantages

- *Heavier than monocoque - lower performance and/or higher fuel consumption.*
- *Less resistant to torsional flexing - compromising handling and road grip.*
- *No crumple zone*

1.5.2.2 Backbone

The backbone tube chassis is a type of chassis that is similar to the body-on-frame design. Instead of a two-dimensional ladder type structure, it consists of a strong tubular backbone (usually rectangular in cross section) that connects the front and rear suspension attachment areas. A body is then placed on this structure.

This type of chassis is also often found on some sports cars. It does not provide protection against side collisions, and has to be combined with a body that would compensate for this shortcoming. [12]

Advantages

- *Strong torsional resistance and ease of manufacture*
- *The vulnerable parts of drive shaft are covered by thick tube. The whole system is extremely reliable, however if a problem occurs, repairs are more complicated.*
- *Modular system that enables configurations of 2, 3, 4, 5, or 6-axle vehicles with various wheel bases*

Disadvantages

- *Manufacturing the backbone chassis is complicated and costly. However if more axles with all-wheel drive are needed, the cost benefit turns in favour of the backbone chassis.*
- *The backbone chassis is heavier for a given torsional stiffness than a monocoque.*

1.5.2.3 Space Frame

A space frame or space structure is a truss-like, lightweight rigid structure constructed from interlocking struts in a geometric pattern. Space frames usually utilise a multidirectional span, and are often used to accomplish long spans with few supports. They derive their strength from the inherent rigidity of the triangular frame; flexing loads (bending moments) are transmitted as tension and compression loads along the length of each strut.

Tubular space frames are widely used in the production of modern motorcycles. Most purpose built race cars used in sports car and stock car racing use tube frame chassis. In the automotive context, space frame construction refers to a design where body panel and other subsystems are assembled onto a structural frame. This differs from a body-on-frame design in that the parts and smaller subassemblies are attached to the frame rather than assembled into a body unit, which is then attached to a frame. [12]

Advantages

- *Very strong in any direction (compared with ladder chassis and monocoque chassis of the same weight)*

Disadvantages

- *Very complex, costly and time consuming to be built.*
- *Impossible for robotised production.*
- *It occupies a lot of space, raises the door sill and results in difficult access to the cabin*

1.5.2.4 Monocoque

Monocoque is a construction technique that supports structural load by using an object's exterior, as opposed to using an internal frame or truss that is then covered with a non-load-bearing skin or coachwork.

Today, a welded unit body is the predominant construction technique. Monocoque designs have also been seen in two-wheeled vehicles, water vessels, and architecture.

The use of composite materials in monocoque skins now allows strength, stiffness and flexibility to be controlled in different directions. Careful design of the direction of the grain of successive layers of materials used in the skin coupled with the use of carbon fibre or other non-isotropic composites can produce different mechanical properties in different directions while optimising for weight.

A halfway house to full monocoque construction was the 'semi-monocoque' used by the Volkswagen Beetle and Citroen 2CV, These used a lightweight separate chassis made from pressed sheet steel panels forming a 'platform chassis', to give the benefits of a traditional chassis, but with lower weight and greater stiffness. [12]

Advantages

- *Cheap for mass production*
- *Inherently good crash protection*
- *Space efficient*

Disadvantages

- *Heavy (unless ULSAB or composite)*
- *Costly and impractical for small-volume production.*

1.5.3 Trailer Systems

1.5.3.1 Traditional Construction

The majority of trailers available on the market today are manufactured using the same basic techniques. A steel frame is welded or bolted together to form a rigid frame and a bed (usually ply-wood or checker plate) is fixed directly to the structure. The other components such as the axle and hitch are simply bolted (or welded) to the chassis. The current caravan chassis is manufactured in a similar manner. This design principle has been around for many years and has proved to be a reliable and cheap method of construction.

1.5.3.2 Composite Construction

Trailer manufacturers are slowly looking into new materials to produce lighter and stiffer products. At present a domestic scale composite trailer is not cost effective due to the infrequent usage and the relatively short distances travelled (estimated on average to be 2000 miles per year [3]). Larger, articulated or semi-trailer, manufactures have begun selling composite based products to a variety of haulage firms across Europe. Significant cost savings are achieved through reduced fuel emissions and reduced maintenance when compared to the steel equivalent (see below).

1.5.4 Articulated Vehicle Systems

1.5.4.1 Traditional Construction

The majority of articulated trailers in use at present are constructed using steel struts to form a rigid frame. This method has proven to be very reliable and cost effective although trailer manufacturers are now looking to use more composite materials in the trailer construction to reduce the trailer mass and gain a competitive advantage.

1.5.4.2 Fully Composite Trailers

Significant research has been conducted in the development of fully composite semi-trailers. Particular publications of worth include Turner and Boyce [13] and Cocker [14].

A 10m urban articulated trailer has been designed as a stand-alone polymer composite chassis onto which different bodies (box or curtain sided) can be attached. The design is 20% lighter than the steel equivalent and provides a great degree of flexibility in the number of end uses and also utilises the weight advantages effectively. The trailer design is based around a monocoque structure, thus maximising the flexibility of the composite materials in reducing weight.

Testing on the proving ground over a variety of surfaces and with various vehicle maneuvers showed that the trailer was very stable and exhibited no unusual behaviour. Strain measurements showed the bending stiffness of the composite trailer to be 18% higher than the steel trailer. Analysis of strain data confirmed the visual and video assessment of the stability of the load bed, with maximum dynamic deflections of less than +/-5 mm. This strain data also confirmed that the main structure was operating well within its strain limits and should therefore suffer no major fatigue problems in service.

1.5.5 Chassis Comparison

Chassis Type	***Weight***	***Cost***	***Stiffness***	***Ease to integrate into caravan***	***Total***
Weighting	*0.4*	*0.2*	*0.3*	*0.1*	*/5*
Backbone	*2*	*3*	*3*	*3*	*2.6*
Body on Frame	*2*	*3*	*3*	*4*	*2.7*
Space Frame	*3*	*2*	*4*	*1*	*2.9*
Monocoque	*4*	*2*	*3*	*2*	*3.1*
Composite Mould	*3*	*1*	*3*	*3*	*3*

Table 1-2: Chassis Comparison

Table 1-2 provides an initial relative comparison of the various chassis systems that are available across a variety of industries. The characteristics are weighted with regard to the main aims of the project (i.e. reducing weight, cost etc.). This gives an early indication into which chassis systems may or may not be appropriate for use on a caravan.

1.5.6 Floor Systems

1.5.6.1 Trailer Floors

The majority of commercial trailer and semitrailer floors are made from widely available traditional materials, the most common being wood laminates. Modern methods of treating and laminating wood mean that the deck is very durable and waterproof. The wooden decking is often topped with a wire mesh to add extra durability. Smaller scale domestic trailers sometime have sheet steel or aluminium floors (checker plate). In nearly all cases the floor is bolted to the steel chassis and does little in the way of adding structural rigidity.

1.5.6.2 Composite Construction

Manufacturers are again turning to composites to develop lighter, stiffer and chemically resistant floors. Conforce, [15], have developed the EKO-FLOR which claims to be 20% lighter than the equivalent plywood floor. The floor is made up from laminates of two outer skins and a core material. The outer skin is typically fibre reinforced plastic (FRP) with the core material usually made from foam or aluminium honeycomb. Major mass production FMCG companies are investing in similar products to reduce their transport costs and improve their environmental credentials. The adaption of a composite floor allows existing chassis structures to be used whilst achieving a significant reduction in weight.

1.6 Project Aim

It is apparent that the present caravan floor, chassis and suspension system has become out-dated and needs to be adapted in-line with the design of the other structural components on the modern caravan. There are a large range of alternative approaches to the design of the caravan chassis and suspension system, many of which are being used in similar industries already. The availability of a range of composite materials on the mass market means that the design options are plentiful and it is therefore important to be mindful of the main requirements of the new system and disciplined in the design approach. It was concluded that the following elements should be considered a priority in the new design. These help to form the basis of a more detailed product design specification:

- Achieve a significant reduction in weight compared with the current chassis, floor and suspension assembly to help achieve improved fuel efficiency and high-speed stability for the tow vehicle.
- Reduce or remove the wood components from the current design to improve weather proofing
- Improve the structural rigidity and integrate the chassis with floor
- Improve the suspension characteristics
- Reduce the overall cost of the assembly (materials + manufacture)

Not all the suspension systems that have been described in this report are suitable for the application to a caravan. Moreover, the suspension system must be designed with consideration to the overall cost of the new chassis and floor. The following table summarises the key characteristics that were deemed to be the most significant when considering the design of the new caravan suspensions system: This was open to review during the design process.

Required Characteristics	***Desirable Characteristics***	***Optional Characteristics***
• *Improved damping and vibrational control when compared with the current system* • *Compact design to fit within existing wheel box* • *Be lightweight (lighter than current design)* • *Reduce tyre wear to a minimum* • *Integrate well with new chassis and floor*	• *Reduce caravan rolling resistance when on tow*	• *Incorporate camber control for improved cornering performance*

Table 1-3: Initial Suspension Specification

The design of the chassis and floor is less constrained than the design of the suspension system. A good understanding of materials and topology optimisation was important in narrowing down the design options. In order to provide a benchmark for comparison it was suggested that the first phase of the project should look to investigate the structural properties of the current caravan floor and chassis design. The following table outlines key characteristics that were deemed to be the most significant when considering the design of the new floor and chassis.

Required Characteristics	***Desirable Characteristics***	***Optional Characteristics***
• *Reduce the overall weight of current set-up* • *Improve the stiffness and rigidity of the current chassis* • *Remove all wood components* • *Minimise the impact on the rest of the services and systems (brakes, overrun, etc.)*	• *Integrate floor with chassis to create a semi-monocoque construction* • *Enable on site manufacture and assembly* • *Environmentally friendly materials and processes*	

TABLE 1-4: INITIAL CHASSIS SPECIFICATION

2 : Initial Experimentation: Chassis

2.1 INTRODUCTION

The current caravan chassis design is a simple, cost effective and relatively robust solution for the majority of mainstream caravan applications in the UK. Despite the wide use of the design within the industry it is regarded as somewhat dated and susceptible to failure when subjected to extreme loading conditions, primarily due to the inadequate suspension characteristics as discussed later in this report. It is believed that the chassis and floor are the main areas where the overall weight of the caravan could be significantly reduced. It is however important that the current stiffness properties are maintained or improved upon when developing the next generation of chassis.

The aim of this study was to investigate the stiffness characteristics of the Alko Vario 2 chassis in combination with a Bailey Unicorn Valencia Caravan Body. The study compared the stiffness of the three stages of caravan construction: i) a chassis and floor, ii) a chassis, floor and body shell and iii) a complete caravan with furniture. The expectation was that the introduction of the body shell and interior furniture would significantly increase the overall stiffness of the structure. The intended output of the study was to develop benchmark comparative stiffness values to aid future design iterations.

The study also compared the stiffness and weight of the current plywood floor with a state of the art GRP composite sandwich panel with a view to using such a material in future designs. It was anticipated that the new GRP laminate would have a superior stiffness to the current floor and would also contribute to a significant weight reduction.

The current caravan chassis is constructed using a 'floor on frame' approach whereby the caravan floor is bolted to a galvanised steel A-Frame, Figure 2-2. The floor is constructed from a plywood-Styrofoam-plywood sandwich and is the de-facto standard amongst the majority of UK caravan manufacturers, Figure 2-1.

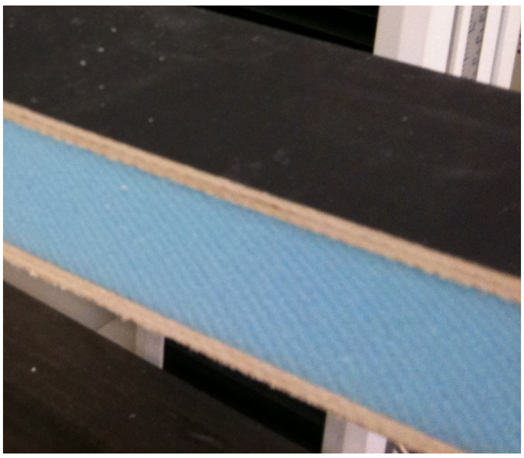


FIGURE 2-1: CARAVAN FLOOR CONSTRUCTION

FIGURE 2-2: FLOOR ON FRAME DESIGN

2.2 CHASSIS STIFFNESS TESTING

The caravan axle was anchored to the floor ensuring that the caravan was unable to move vertically. This meant that, as each point was loaded, the chassis would bend rather than lift. Each test specimen was subjected to vertical loading at two separate points as highlighted in Figure 2-3 below. The load points remained constant in each test so that a relative comparison of stiffness could be generated.

The load was applied gradually and the displacement was recorded.

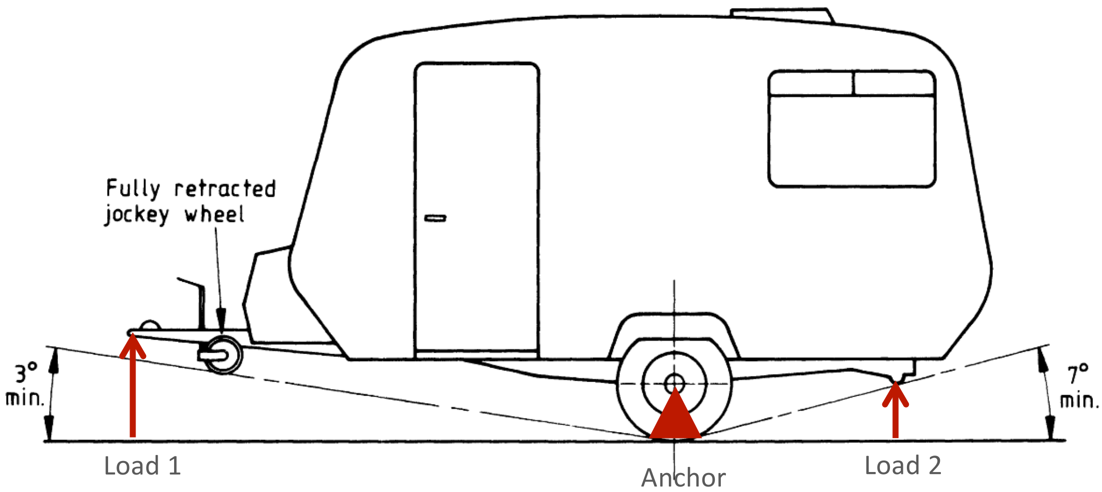


FIGURE 2-3: CARAVAN LOADING SCHEMATIC

2.2.1 No Shell

The first stage of testing involved loading a chassis and floor assembly at the two different locations outlined in 2.2 above.

Figure 2-4: Chassis Loading

As the structure was loaded the chassis frame began to twist inwards and away from the floor as shown in Figure 2-5 below.

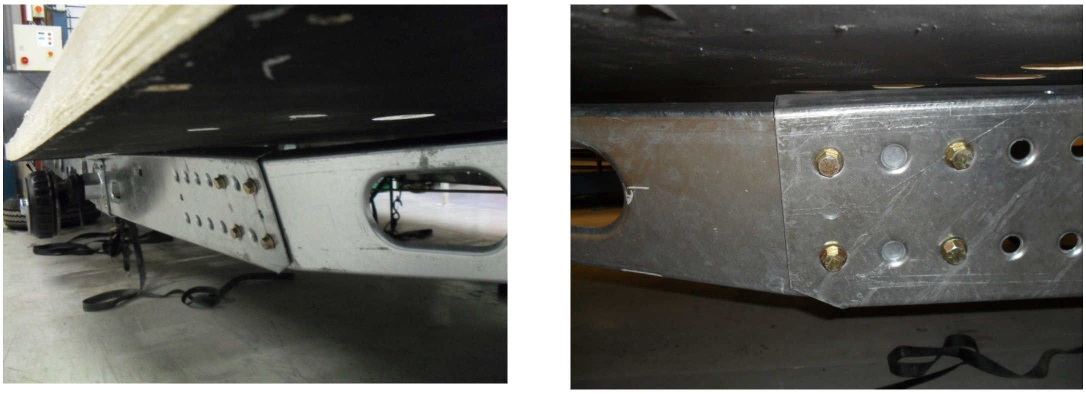


Figure 2-5: Chassis Bending

2.2.2 With Shell (No Furniture)

The second stage of testing incorporated the body shell on the chassis and floor sub-structure, Figure 2-6. The test was repeated using the same method as before in order to analyse the effect of the body shell on the overall stiffness.

FIGURE 2-6: HITCH LOADING ON SHELL

2.2.3 WITH SHELL AND FURNITURE

The third stage of testing incorporated simple furniture set into the shell as shown in Figure 2-7 below. It was anticipated that the furniture would provide extra bracing within the structure and hence increase the overall rigidity of the caravan.

FIGURE 2-7: INTERIOR FURNITURE

2.2.4 Chassis Results

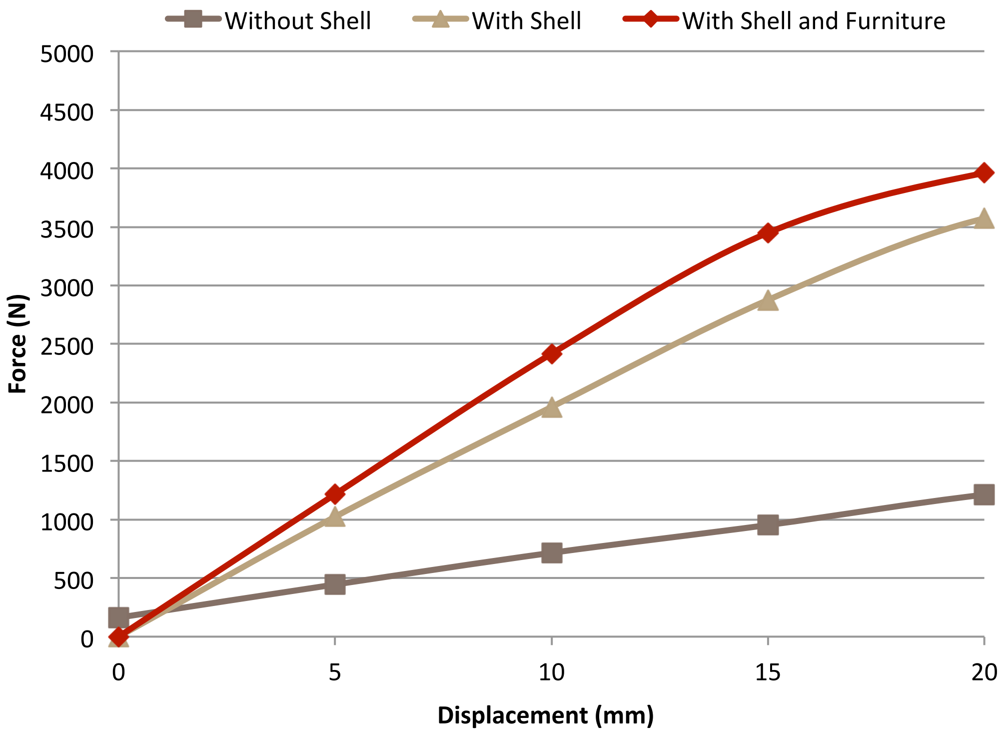


FIGURE 2-8: HITCH LOADING RESULTS

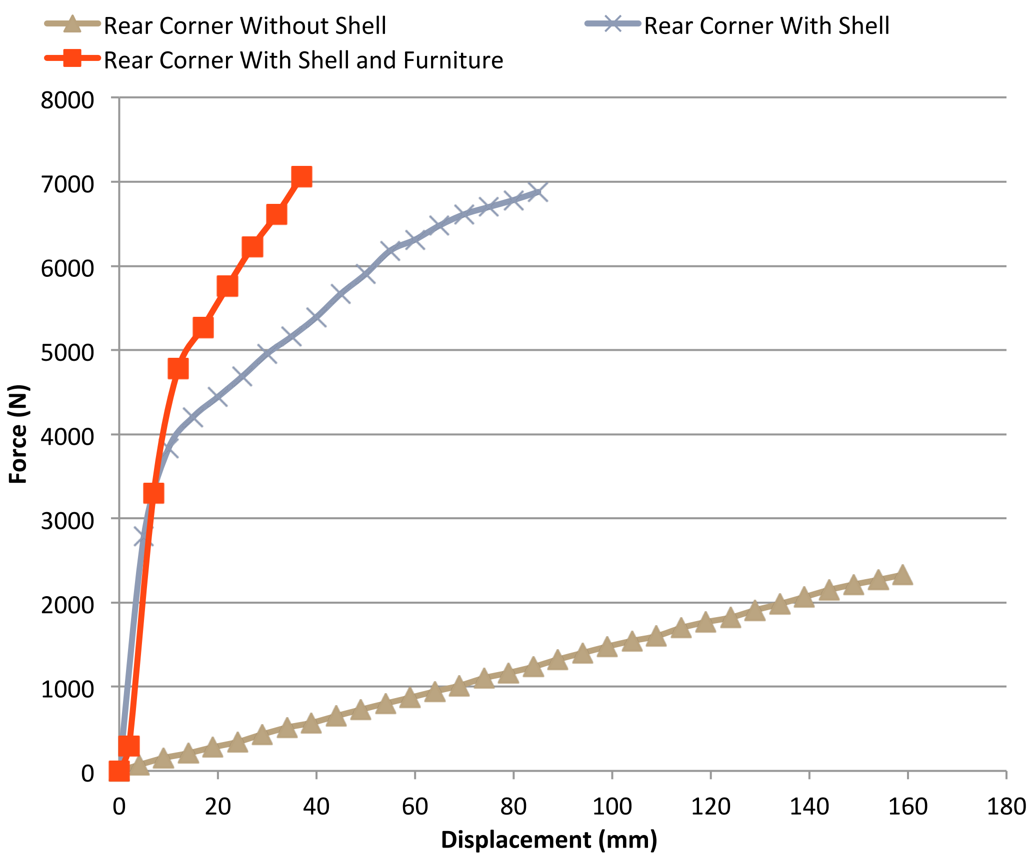


FIGURE 2-9: REAR CORNER LOADING RESULTS

2.2.5 Chassis Stiffness Discussion

Figure 2-8 and Figure 2-9 above indicate that the stiffness of the caravan chassis is influenced by both the body shell and the installation of the interior furniture. It is apparent that the addition of the body shell to the floor and chassis results in a marked increase in stiffness that varies according to the location of the load. The addition of the furniture again increases the stiffness of the overall structure but not by the same magnitude as the body shell.

The performance of the chassis is greatly affected by the body shell, which acts as a set of stiffening struts over the length of the floor. This additional strength may be partly attributed to the Alu-Tech construction of the body and may be less evident in other manufacturers products; however, it should be accounted for when developing the next generation of caravan chassis.

2.3 Floor Test

The current floor design, Figure 2-10, was compared with a new reinforced GRP sandwich panel, Figure 2-11, using a simple three point bending test on a complete, full size floor. This provided an idea of the stiffness of each floor compared with their respective weights. It was anticipated that the GRP panel would show a substantial increase in stiffness compared with the current plywood floor but would also be significantly heavier. The test would indicate whether there was the potential to remove the galvanised steel chassis frame by introducing a stiffer floor structure (thus decreasing the net weight of the caravan) and creating a more ‘monocoque’ design.

Figure 2-10: Ply Floor

Figure 2-11: Kemlite GRP Floor

2.4 Floor Stiffness Results

Ply Floor Weight – 94.2kg (Unicorn Valencia), Max Load at mid span -15kg

Kemlite GRP Floor Weight – 170kg (Unicorn Valencia), Max Load at mid span - >260kg

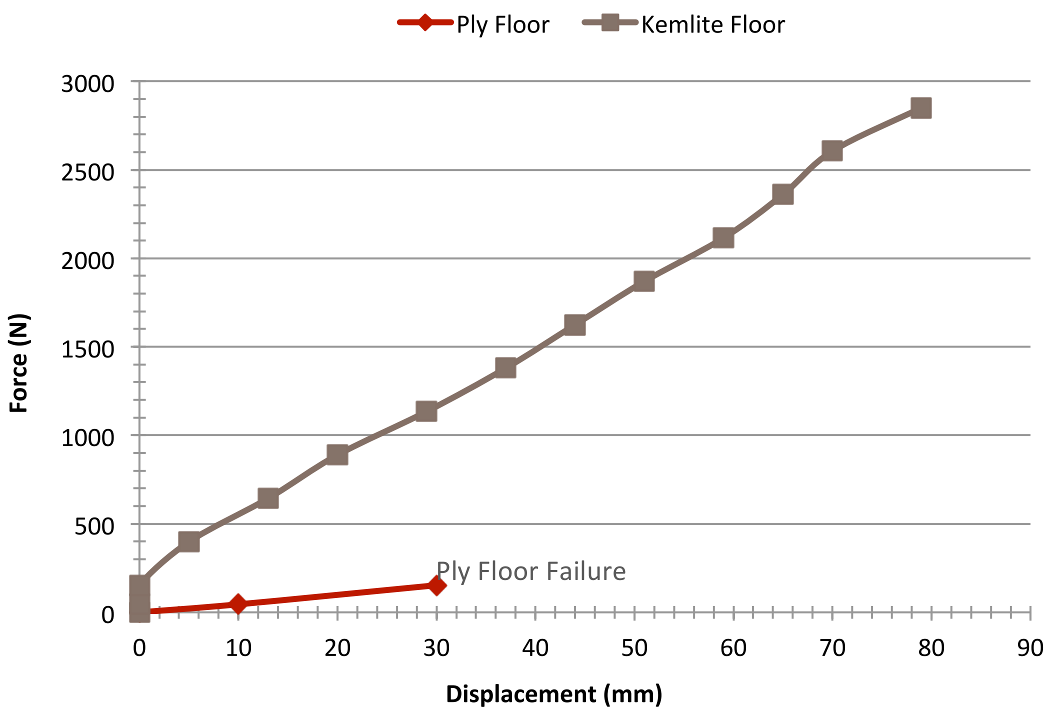


Figure 2-12: Floor Stiffness

The plywood floor was almost unable to support its own weight, was very flexible and failed at a load of 15kg, Figure 2-13. The Kemlite GRP floor was substantially stiffer as shown in Figure 2-12 and did not fail with a 290kg load (maximum available), Figure 2-14.

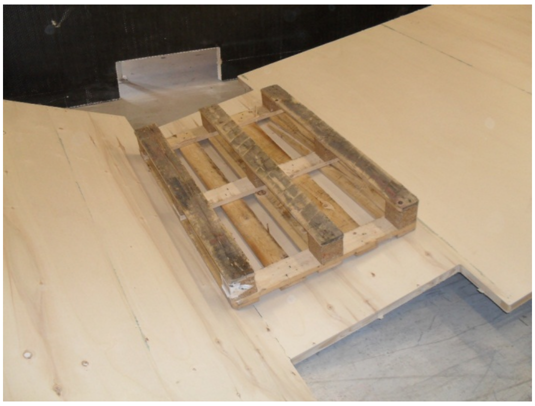


Figure 2-13: Ply Floor Failure

Figure 2-14: GRP Floor Supporting 290Kg

2.4.1 Floor Stiffness Discussion

The plywood floor that is used for current caravan construction failed under a central load of 15kg. It was also observed that the floor struggled to support its own weight and may have failed through creep if left for a few hours. This indicates that the floor offers little in terms of structural rigidity and relies heavily on the steel chassis and caravan body shell for strength. The floor is, however, significantly lighter than the GRP floor and even when the steel chassis (weighing approximately 70kg without suspension) is attached there is still a slight weight saving.

The Kemlite GRP floor is almost twice as heavy as the plywood floor but approximately 7 times stiffer. The floor did not fail with a central load of 290kg. It should be noted that the Kemlite floor, which is made up of resin beams contained within GRP outer panels, is not intended for caravan floor applications and a weight saving could be generated if the design were to be optimised. Figure 2-15, below, compares the mid-span stiffness of the ply floor and steel frame against the Kemlite floor. The results show that there is the potential to use a stiff floor structure in place of a steel frame but the challenge lies in reducing the floor weight.

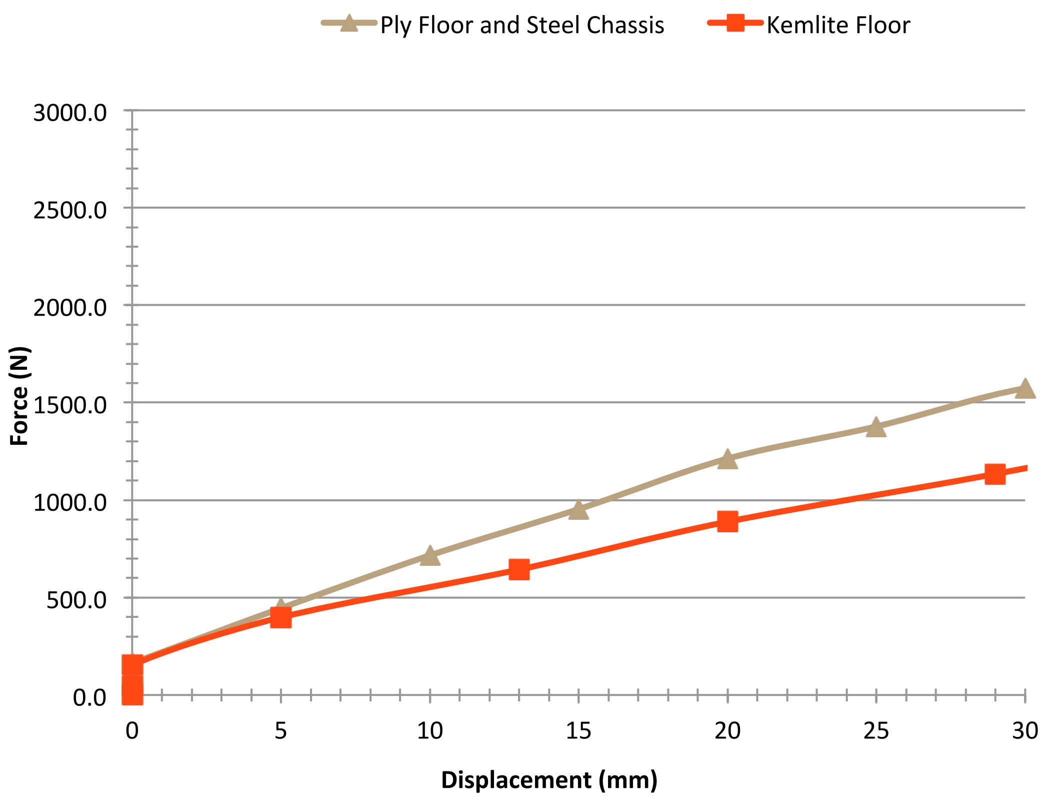


FIGURE 2-15: CHASSIS STIFFNESS COMPARISON

2.5 Conclusions

The results from the static stiffness tests have shown that there is the potential to reduce the 'bulk' of the 'floor on frame' chassis structure through the use of a stiff composite floor. It was shown that the body shell dramatically increases the stiffness of the caravan structure and that the addition of furniture also results in an increase in overall rigidity. It is therefore reasonable to conclude that there is strong potential to create a complete monocoque structure through the development of a stiff but lightweight caravan floor. The application of sandwich panel composites lends itself well to the design of rigid lightweight structures however the potential materials for the makeup of such a structure are vast and this should be investigated more thoroughly. Consideration should also be paid to the ability of the material to withstand point loads from the suspension system during caravan transit.

The following chapter investigates the suspension characteristics of the current system with a view to establishing a set of benchmark parameters.

3 : Initial Experimentation: Suspension Performance

3.1 Introduction

The design and configuration of caravan suspension has changed little over the past 25 years and the current system is perceived to be a reliable and robust way of ensuring caravan stability and vibration isolation when on tow. Early suspension systems consisted of a trailing arm with a coil spring and damper, Figure 3-2, and were regarded to be a simple but effective way of isolating road vibration. However, it was believed that this system took up too much space in the caravan's interior and was consequently superseded by the more compact design that has been used since the late 1980's. The current favoured design consists of a trailing arm with a torsional rubber spring contained within an axle tube and a separate damper, Figure 3-3. Over recent years the lack of development in caravan suspension systems has caused manufacturers to pose questions into its suitability for the modern product. Road testing, conducted in 2009 by Bailey during the development of their Alu-Tech system, indicated that in extreme road conditions the chassis could crack, ultimately leading to structural failure, Figure 3-1.

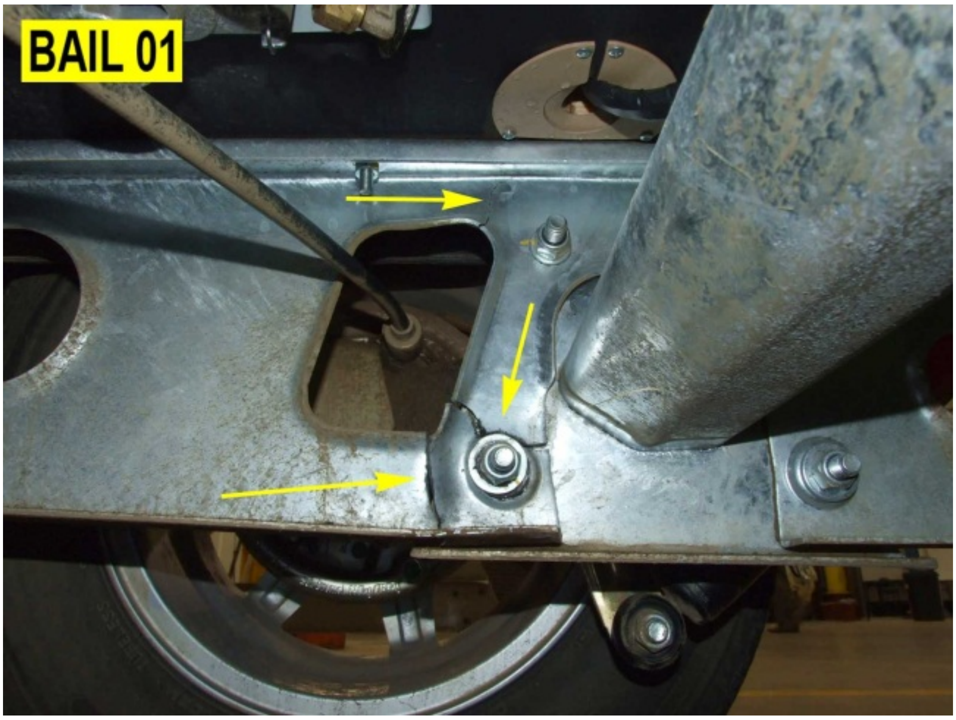


Figure 3-1: Chassis Failure

Previous research has indicated that a similar suspension system used on a 1994 caravan had a stiffness value four times that of a standard road car [8]. It has been suggested that this high stiffness results in forces being transmitted through the suspension that exceed the design loading condition of the chassis when the caravan is subjected to extreme road conditions.

It is the intention of this chapter to investigate the performance of the current suspension with a view to highlighting key areas of potential improvement. The chapter includes analysis of in-house stiffness testing, damper testing and road testing at a vehicle proving ground.

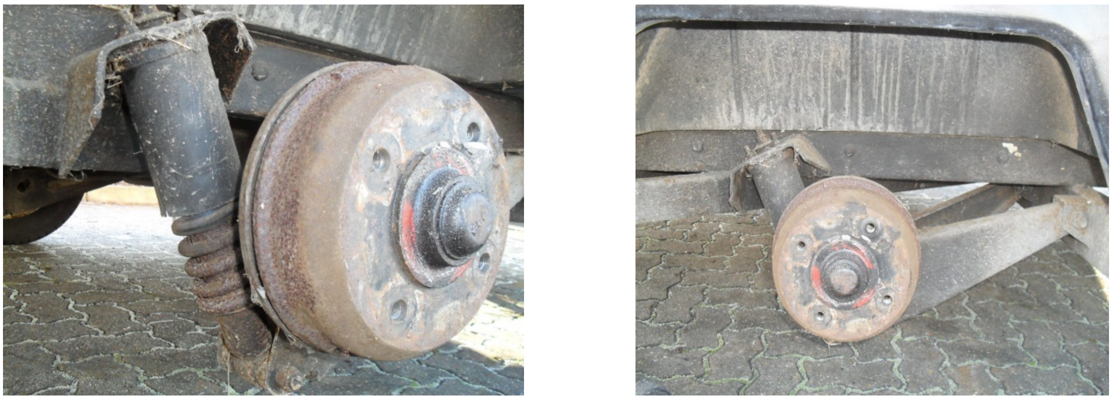


FIGURE 3-2: TRADITIONAL CARAVAN COIL SPRING SUSPENSION

FIGURE 3-3: MODERN CARAVAN SUSPENSION

At present all of the caravan manufacturers in the UK use a torsional rubber suspension system to isolate road vibrations when the caravan is on tow. The suspension and chassis are supplied as one kit and are assembled on site upon delivery. As mentioned previously, within the UK, Alko who share around 80-90% of the market, predominantly supplies this suspension system. The remainder of the share is attributed to BPW who use similar design principles to the Alko system [16].

This investigation was conducted using the Alko suspension assembly that is common on the majority of caravans. The suspension consists of a torsional rubber tube contained within a hollow cross member that connects to each side of the chassis, Figure 3-4. As the wheel encounters a bump or hollow the axle turns and compresses the rubber, which exhibits a damped spring characteristic. There is also an additional shock absorber located on the swing arm that claims to provide further damping, Figure 3-3.

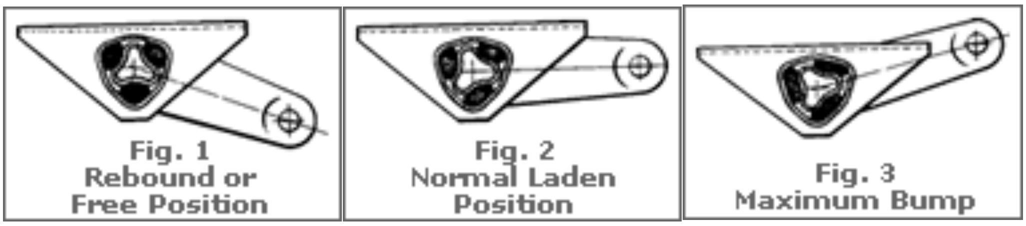


FIGURE 3-4: SUSPENSION POSITIONS [6]

It is believed that this system provides inadequate vibration isolation from road defects [8] and it is the intention of this chapter to analyse the performance and suggest possible improvements.

All testing was based on the Bailey Unicorn Valencia with the following properties:

Variable	Mass
Mass in Running Order	*1409 kg*
Maximum Laden Mass	*1565 kg*
Max Pay Load	*156 kg*
Max Chassis Load	*1600 kg*
Max Tyre Load	*1800 kg*
Tyre Pressure	*62 psi*
MRO Nose Weight	*88 kg*

TABLE 3-1: UNICORN VALENCIA PROPERTIES

3.2 PREVIOUS TESTING

Previous research conducted by Fratila [8] and McDonald [9] has shown that a similar suspension system used on older caravans exhibits an equivalent spring stiffness of approximately 88kN/m at the wheel. Given that the design of the suspension has changed little since this initial research it can be assumed that the stiffness has remained constant however it was considered important to verify these results with independent testing.

The present suspension manufacturers also supply an optional shock absorber, Figure 3-3, which claims to provide additional damping to the suspension system. The characteristics of this damper were also investigated.

3.3 Torsional Rubber Suspension Stiffness

The chassis was raised on all of the corner steadies so that the wheels were off the ground and the suspension was fully unloaded. The wheels were then removed and the axle tube was strapped to the ground, Figure 3-5, preventing it from moving vertically. The suspension swing arm was then loaded under the drum brake using a jack located on a load cell.

Figure 3-5: Test Setup

The load was measured against the vertical displacement allowing the wheel rate to be calculated.

3.3.1 Results

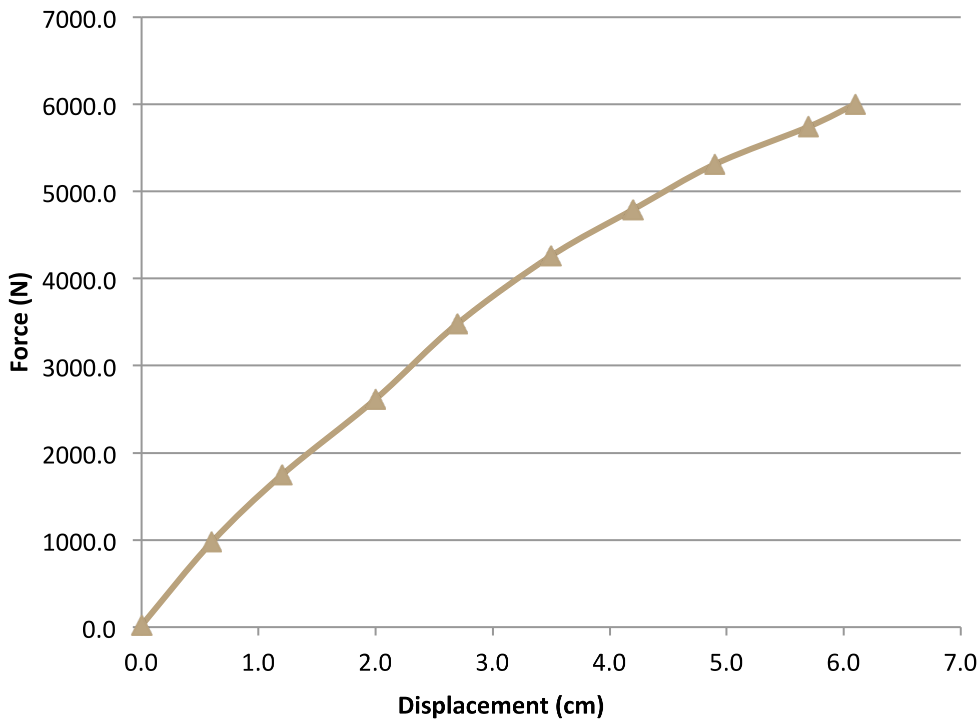


Figure 3-6: Wheel Rate of Alko Suspension

3.3.2 DISCUSSION

The wheel rate is shown to be approximately 90kN/m, which suggests that that the system used in the present design has changed little since Fratila's study in 1994. It is worth noting the limited suspension displacement available from this design. A normal road vehicle has over 150mm travel from bump to rebound while this had less than half this value. Although not apparent in this static test, it is likely that hysteresis within the rubber would result in a degree of damping that would be helpful in terms of suspension behaviour.

Having established the wheel rate it is now possible to calculate the natural frequency of the sprung mass system. From a ride comfort point of view, standard automotive systems usually aim to achieve a natural frequency of around 1-1.5 Hz [17] and anything above this value will result in a harsher ride quality.

$$\omega_0 = \sqrt{\frac{k}{m}}$$

$$\omega_0 = \sqrt{\frac{90{,}000}{660.5}}$$

$$\omega_0 = 11.67\text{rad/s} = 1.86\text{Hz}$$

The natural frequency for this system is significantly above a typical design value for a standard car on British roads indicating that the wheel rate is too high and/or the mass is too low. This is likely to result in poor vibration isolation and harsh ride characteristics when the caravan is on tow.

3.4 DAMPER TESTING

The Alko shock absorber was cycled at different frequencies in a damper dynamometer sinusoidal displacement test rig, Figure 3-7. The damper-force, displacement and velocity were sampled at a rate of 1000Hz over a period of two seconds per test. A force vs. velocity graph was produced for each of the frequencies. The test was repeated with two different dampers of the same specification to ensure that the results were reliable. The results were collated and a force vs. velocity profile was produced over the entire frequency range, Figure 3-8.

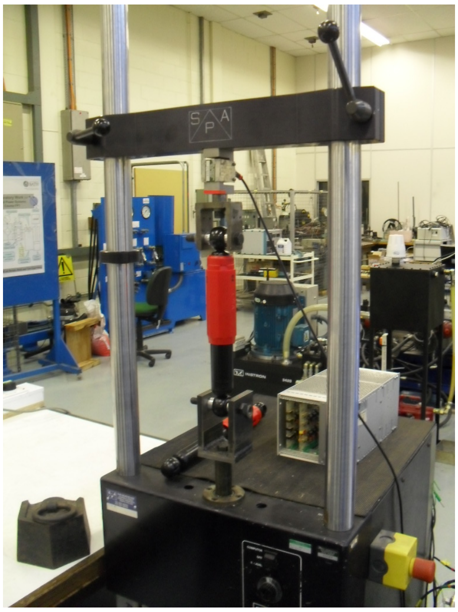


Figure 3-7: Damper Test Rig

3.4.1 Results

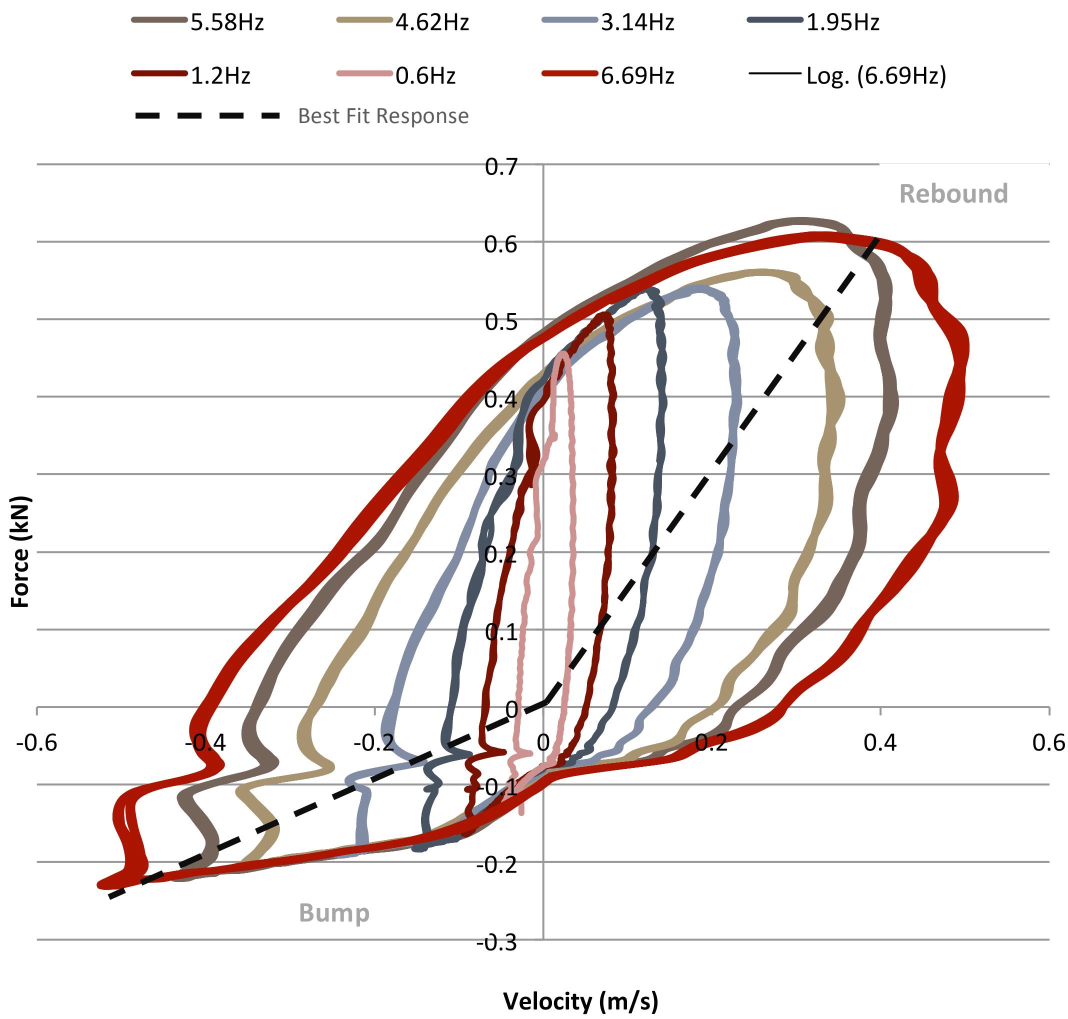


Figure 3-8: Alko Damper Profile

3.4.2 Discussion

Figure 3-8 shows that the Alko shock absorber does not exhibit the characteristics of a typical damper. The deviation from the approximate 'best-fit' is somewhat greater than that seen in the majority of modern shock absorbers. This can be attributed to its simpler design, which results in abnormal oil and airflows through the internal orifices.

The approximate damping rates in bump and rebound can be calculated from the gradient of the 'best-fit' lines.

Bump:

$$c_b = \frac{dF}{dV}$$

$$= \frac{230}{0.52}$$

$$= 442Ns/m$$

Rebound:

$$c_r = \frac{dF}{dV}$$

$$= \frac{590}{0.43}$$

$$= 1{,}372Ns/m$$

Using these values it is now possible to calculate the damping ratios in bump and rebound based on the measured spring stiffness at the wheel and the mass of the caravan. A typical damping ratio for road car suspension is approximately 0.25 [17] and it is reasonable to assume that a caravan should exhibit a similar value. The damper pivot was positioned at approximately the same distance from the axle as the hub giving a 1:1 lever ratio.

Caravan natural frequency:

$$\omega_0 = \sqrt{\frac{k}{m}}$$

$$\omega_0 = \sqrt{\frac{90{,}000}{660.5}}$$

$$\omega_0 = 11.67\text{r/s} = 1.86\text{Hz}$$

Damping Ratio in Bump:

$$\xi_b = \frac{c_b}{2m\omega_0}$$

$$\xi_b = \frac{442}{15{,}420}$$

$$=0.029$$

Damping Ratio in Rebound:

$$\xi_r = \frac{c_r}{2m\omega_0}$$

$$\xi_r = \frac{1{,}372}{15{,}420}$$

$$=0.089$$

The damping ratios in both bump and rebound are very significantly lower than would be expected for a road vehicle of this type even when accounting for the shock absorber rubber mounting bushes. The results show that the Alko shock absorber has little to no effect on the damping of the suspension system. The majority of damping comes from the natural hysteresis of the rubber as it is loaded. To increase the damping ratio to achieve a value of around 0.25 the spring rate should be reduced and the damping rates increased.

3.5 Performance Testing

In order to establish an understanding of how the suspension performed on a variety of surfaces the caravan was sent to Millbrook Proving Ground; a vehicle test facility in Bedford. The test centre at Millbrook recreates common road conditions that a caravan may encounter throughout its life. Such conditions include; potholes, sleeping policemen, cobbled roads, curbs, winding roads and a high-speed bowl (motorway). The test completed by the caravan in this instance is identical to that undertaken by car manufacturers to ensure that the vehicle is of sufficient build quality to be sold to the general public. The test has been designed to recreate 6,000 miles of heavy use on normal roads and is broken into a number of sections as shown in Table 3-2.

Test	Speed	Cycles	Test Distance
Pave’	10 mph	231	207.9 miles
Kerb Strikes	5 mph	63	31.5 miles
Hill Route	n/a	30	63.0 miles
Twist Humps	10 mph	99	118.8 miles
High Speed	n/a	51	214.2 miles
Potholes	15 mph	24	21.6 miles
Total Distance			657.0 miles

Table 3-2: Test Details

The aim of the test was to allow the data from the control tests to be compared with real life conditions to establish what loads the suspension and chassis are encountering. The benefit of using such a facility is that the tests can be easily controlled, repeated and monitored in order to obtain an accurate data set.

A set of three tests conditions were analysed in detail:

- Kerb Strikes
- Pot Holes
- Belgian Pave (Cobbled Street)

3.5.1 Experimental Setup

The caravan was fitted with a linear displacement transducer on the off-side wheel that measured the displacement of the wheel hub. The transducer was linked to an on-board data logger that sampled the signal at 100Hz.

3.5.2 Curb Strike

3.5.2.1 Test Procedure

The car and caravan were accelerated to 5mph and were driven over the 30° kerb. The right hand side of the car and caravan passes over curb A first followed by the left hand side over kerb B, Figure 3-9. The kerb is 100mm high with a 90° edge. The test was repeated to ensure accurate and reliable results.

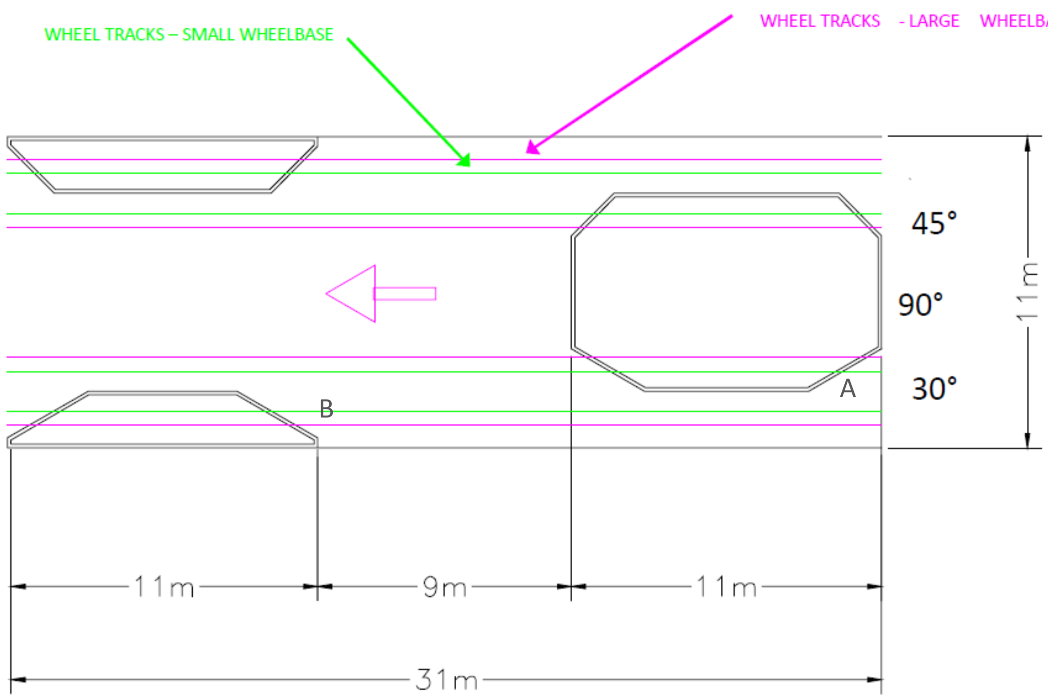


Figure 3-9: Curb Strike Plan View Layout

3.5.2.2 Results

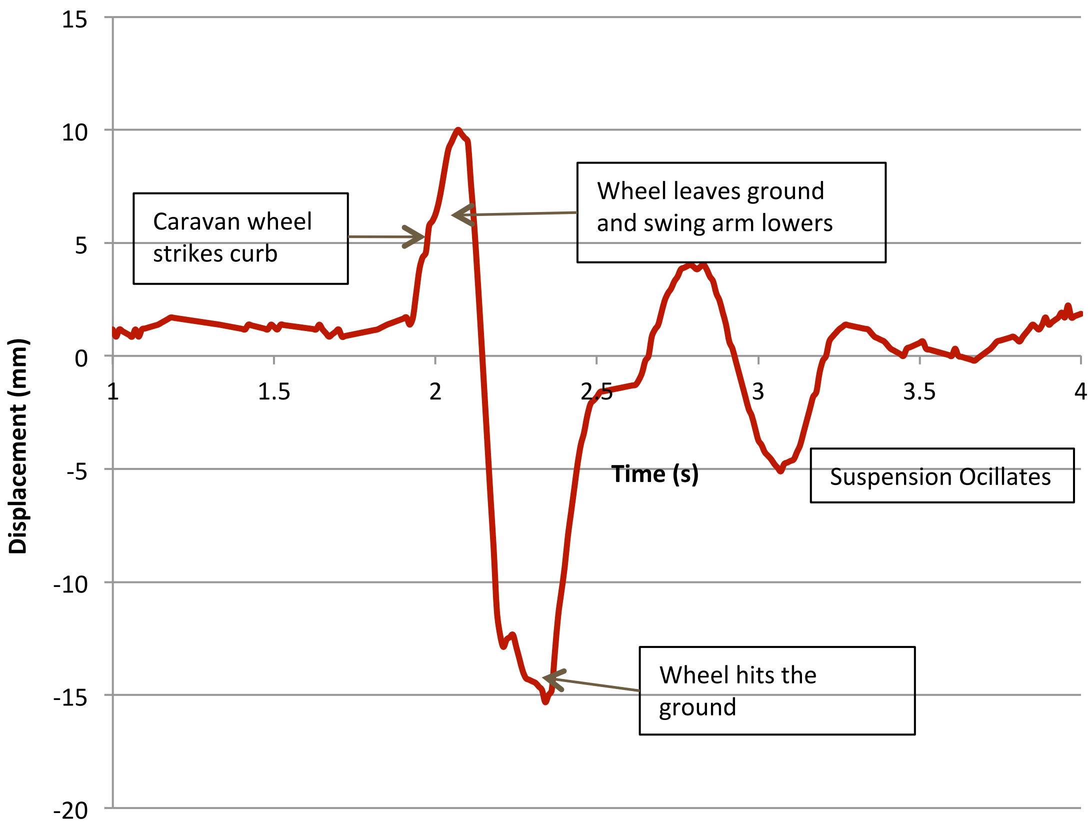


Figure 3-10: Curb Strike Hub Displacement

3.5.3 Pot Hole

3.5.3.1 Test Procedure

The car and caravan couple was accelerated up to 15mph and passed through two potholes (A and B) as shown in Figure 3-11 The potholes are of the dimensions shown in Figure 3-12an d are 1.22m wide.

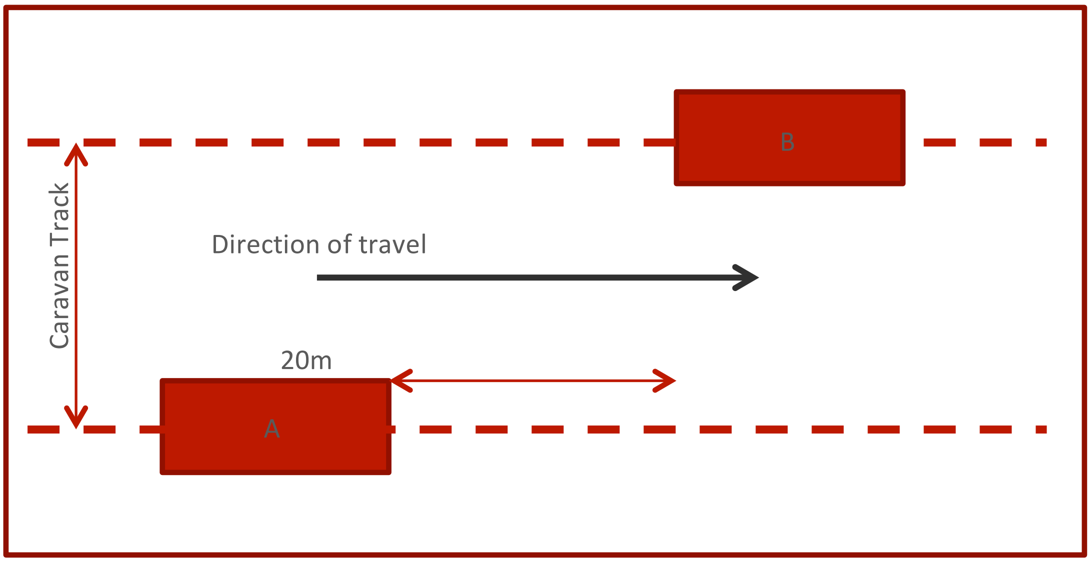


Figure 3-11: Pothole Test Layout

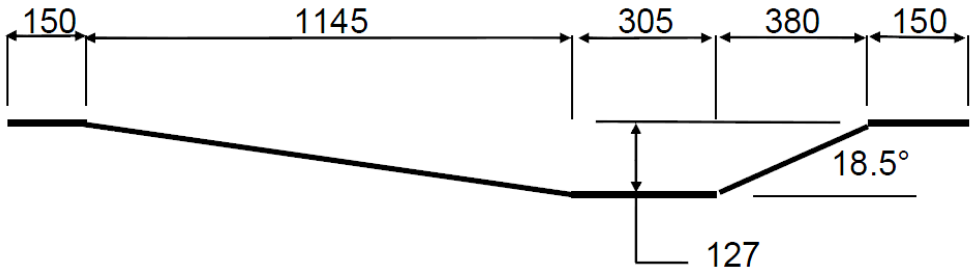


FIGURE 3-12: POTHOLE DIMENSIONS

3.5.3.2 RESULTS

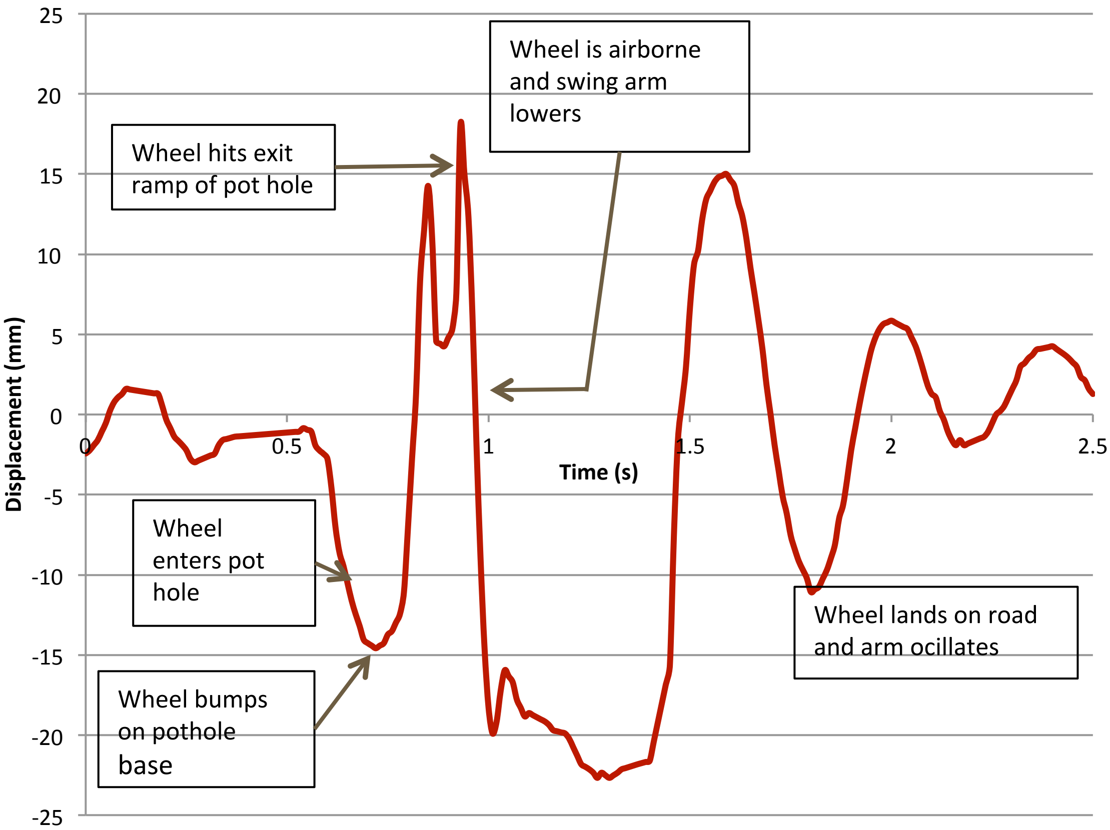


FIGURE 3-13: POTHOLE HUB DISPLACEMENT

3.5.4 Belgian Pave

3.5.4.1 Test Procedure

The Belgian pave test facility consists of 1.5km of cobbled stone track with drainage ditches located at regular intervals. The car and caravan travel around the circuit at 10mph.

Figure 3-14: Pave' Road

3.5.4.2 Results

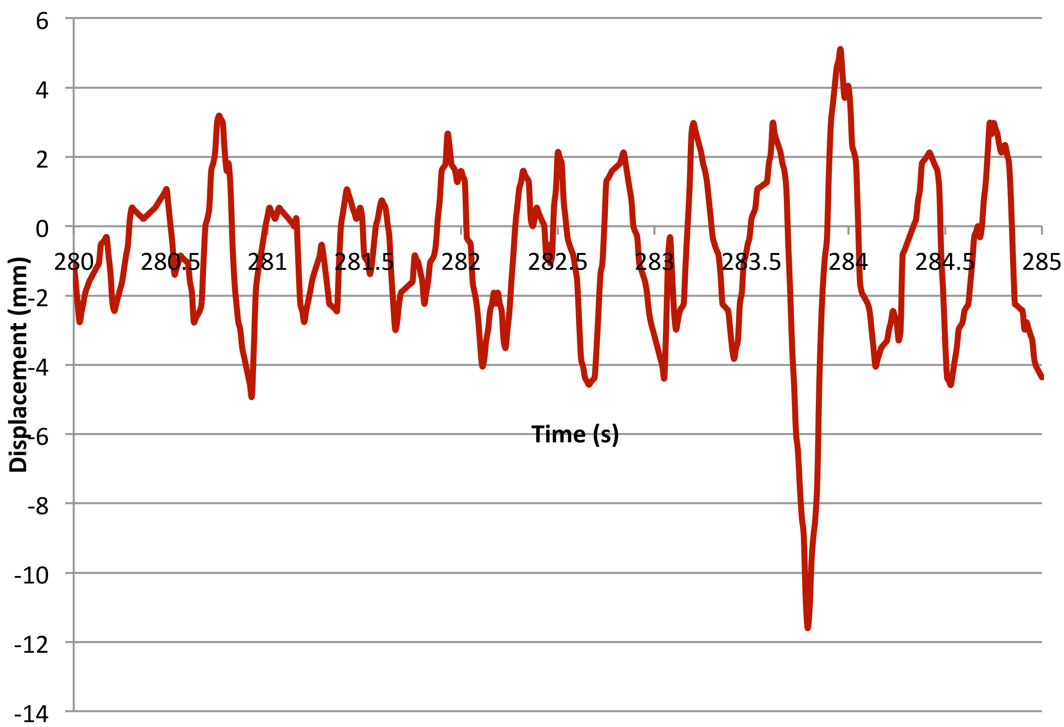


Figure 3-15: Hub Displacement over Pave' Section

3.6 Conclusion

From the figures above it can be seen that the pothole test results in the largest displacement of the hub achieving a value of around +18/-22 mm. Given the severity of the impact during this test in which the wheel left the ground it would be reasonable to expect a much larger displacement, closer to the maximum (claimed) design value of 50mm. This indicates that the current suspension stiffness is too high and should be reduced to facilitate greater travel. This is also suggested by the fact that the natural frequency of the caravan system is significantly higher than a typical passenger road car. Furthermore, following video analysis, it can be seen that during the pothole impact the tyre compresses almost to the wheel rim and upon exit the caravan is launched into the air, Figure 3-16.

Figure 3-16: Caravan Bump in Pothole

Continued driving of the caravan around the proving circuit caused the nuts connecting the axle tube to the main chassis member to become loose. This resulted in the bolts being able to move and transfer stress to the boltholes leading to the propagation of cracks in that area, Figure 3-17. The caravan was only able to complete 47% of the tests outlined in Table 3-2 before it was unsafe to use.

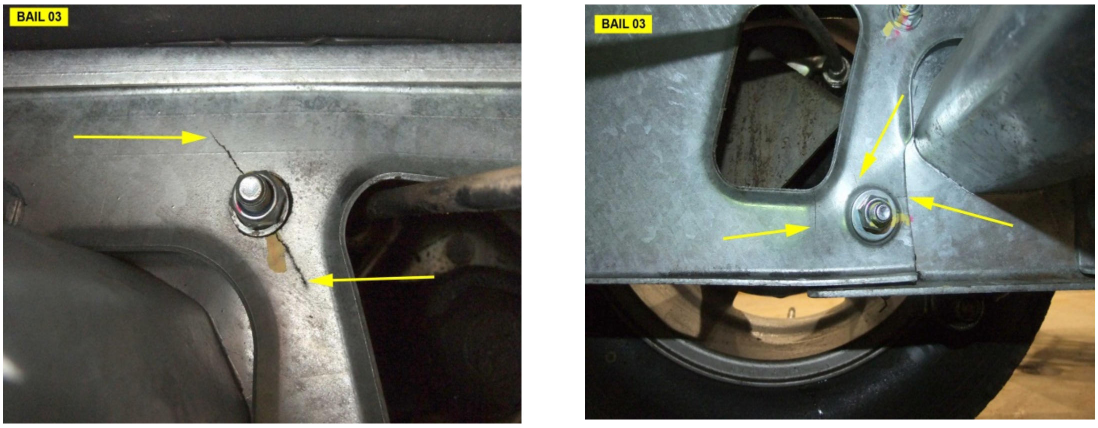


FIGURE 3-17: CHASSIS FAILURE

It should be noted that during these tests the caravan was unloaded and in normal use the caravan mass would be increased. While this may result in the suspension stiffness better matching the mass requirements it is likely that the caravan would have failed sooner than documented here. Nevertheless it is reasonable to conclude that the current design parameters of the suspension system are not optimum and result in excessive loading on the caravan chassis in certain road conditions.

3.7 RECOMMENDATIONS

In order to improve the suspension system it was recommended that the suspension components are adapted to meet the following design parameters:

- A maximum natural ride frequency of 1.5Hz resulting in a wheel rate of 58.7kN/m
- A minimum damping ratio of 0.25 resulting in an average damping rate of 3000 Ns/m
- Minimum total wheel travel of 60mm.

These parameters are based on the Bailey Unicorn Valencia model and will have to be adapted to suit other caravan sizes. In order to facilitate these changes it was recommended that the suspension configuration be changed to include a coil spring and damper assembly. A number of caravan manufactures in Australia use trailing arm systems Figure 3-18, which offer a simple, easily maintainable and effective solution. It was recommended that a system of this type be considered as a replacement for the current design.

FIGURE 3-18: TRAILING ARM COIL SUSPENSION

3.8 NEXT STEPS

A system similar to the type shown in Figure 3-18 was used on British caravans up until the early 1980's. It was recommended that a caravan with this suspension system be subjected to the pothole test to analyse its performance and compared with the results in this chapter. The spring and damper rates would be calculated and the system could then be optimised based on the parameters mentioned above and transferred into a working prototype for further analysis.

4 : Investigation of a Caravan with Coil Spring Suspension

4.1 Introduction

This chapter follows on from the investigation in to the Alko rubber torsion suspension system in chapter 3 and investigates the performance characteristics of a 1982 caravan damped coil spring suspension assembly. The system, which is now redundant in modern caravan design, comprises of a trailing arm with a coil-over-damper arrangement as shown in Figure 4-1 below.

Figure 4-1: Traditional Caravan Suspension

The system was widely seen in caravans of the early 1980's until it was replaced by the present day setup, which aimed to be more space efficient and cost effective. Despite the more compact design the new suspension system has several flaws as highlighted in chapter 3. It also is believed that the space saving characteristics of the present design are negligible and that advances in materials and damper technology now present the opportunity to revert back to the original arrangement without compromising on cost or increasing bulk. The trailing arm system is regarded to be a simple design that is easily serviceable and offers the capability of more precise tuning thus greatly improving the ride characteristics of the caravan. Moreover, it is widely used within the Australian caravan market and is also commonly used for the rear suspension of many small to medium hatchback cars [10].

This investigation comprised of a number of tests that examined the spring and damper rates of the suspension components and compared the results to the current suspension system. The study also included a pothole test as described in chapter 3 to provide an in-use comparison. The relatively lightweight caravan used is a 1982 Sprite Alpine Clubman, Figure 4-2, has mass properties as outlined below.

MRO	738kg
Nose Weight	38kg
Weight over wheel	350kg

FIGURE 4-2: 1982 SPRITE ALPINE CLUBMAN

4.2 EXPERIMENTAL TESTING

4.2.1 SPRING AND DAMPER RATES

4.2.1.1 SPRING RATE

The coil spring was removed from the caravan and placed in a tensile test machine and compressed by 40mm. The load and displacement were recorded as shown in Figure 4-3.

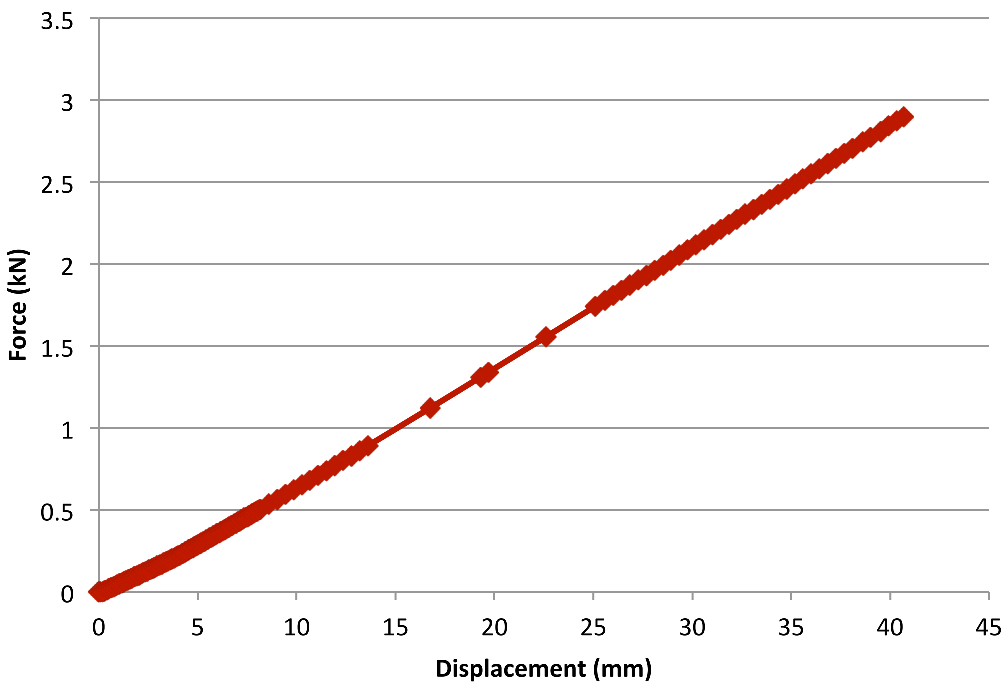


FIGURE 4-3: COIL SPRING RATE

$$k = \frac{F}{x}$$

$$= \frac{2840}{0.039}$$

$$72.8kN/m$$

This value is equal to the spring stiffness and is not the same as the wheel rate, which is needed to calculate the sprung mass natural frequency. The wheel rate accounts for the lever ratio produced by the swing arm geometry.

4.2.2 Wheel Rate

The wheel hub was loaded and the displacement of the hub and coil were measured at regular intervals. As the caravan was not secured to the ground the results were only reliable until the applied load exceeded the weight of the caravan (when the caravan began to lift off the floor).

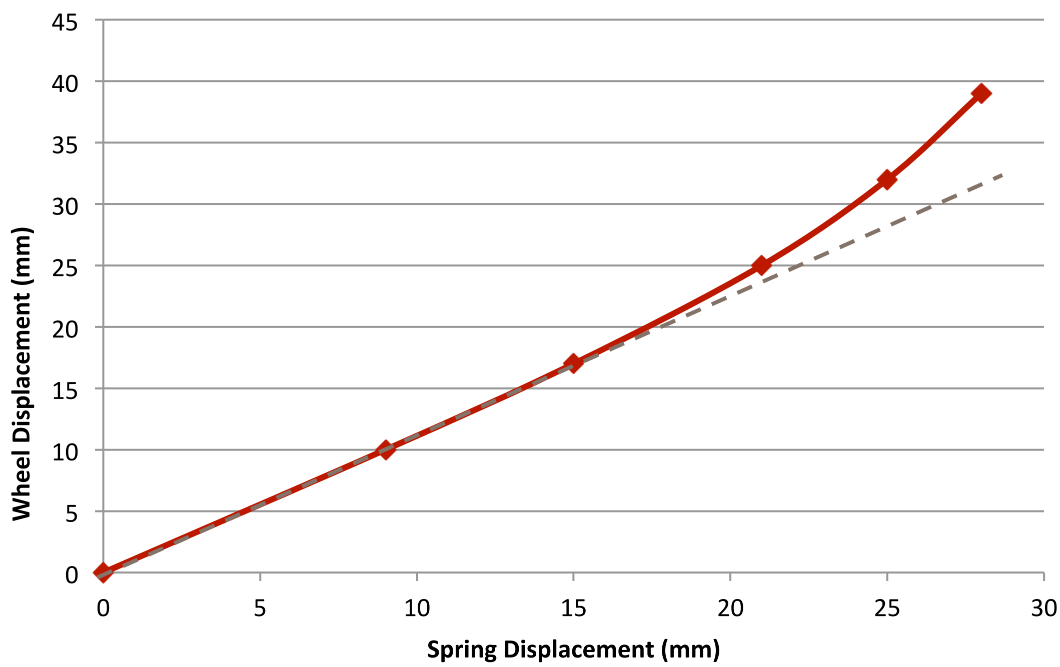


Figure 4-4: Spring vs. Wheel Displacement

The dashed line in Figure 4-4 indicates the closest relationship between the wheel hub displacement and the spring compression. This has accounted for the lifting of the caravan when the load is applied. The spring compression is shown to be approximately 0.9 of the wheel displacement (λ=1.1). The corresponding wheel rate can now be calculated.

$$k_w = \frac{k_s}{\lambda^2}$$

$$k_w = 72.8 * 0.81$$

$$= 59.0kN/m$$

4.2.3 Damper Rate

The shock absorber was removed from the caravan and tested in a damper dynamometer sinusoidal displacement rig at varying frequencies. The velocity, load and displacement were recorded.

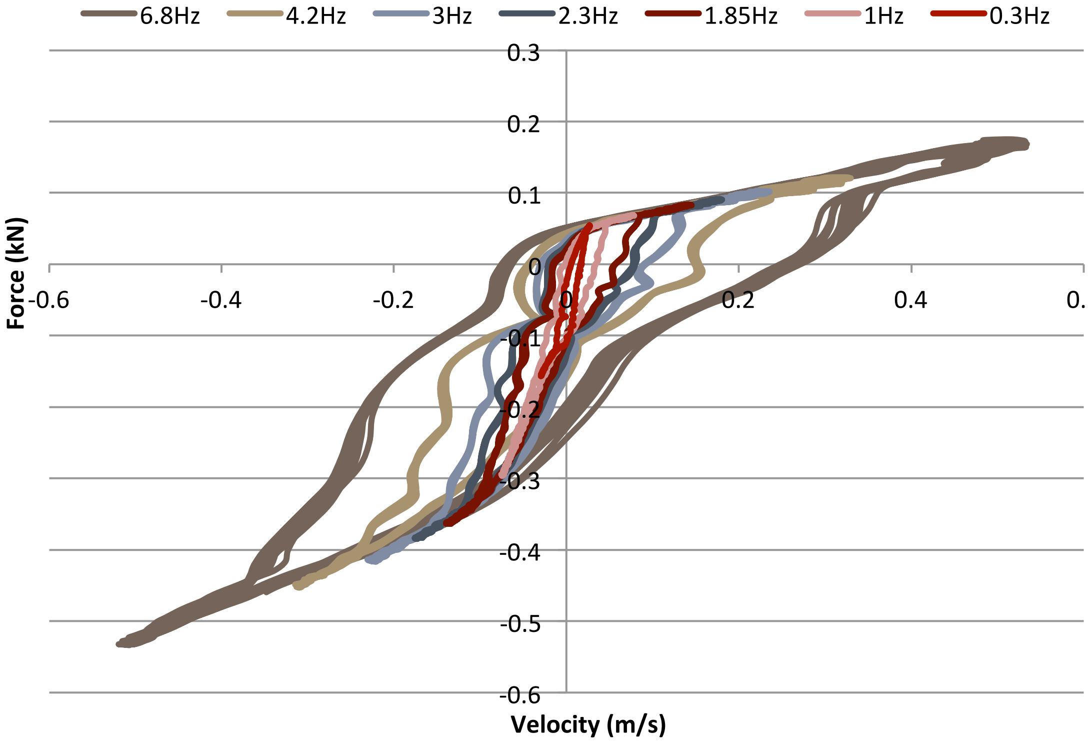


Figure 4-5: Sprite damper Characteristics

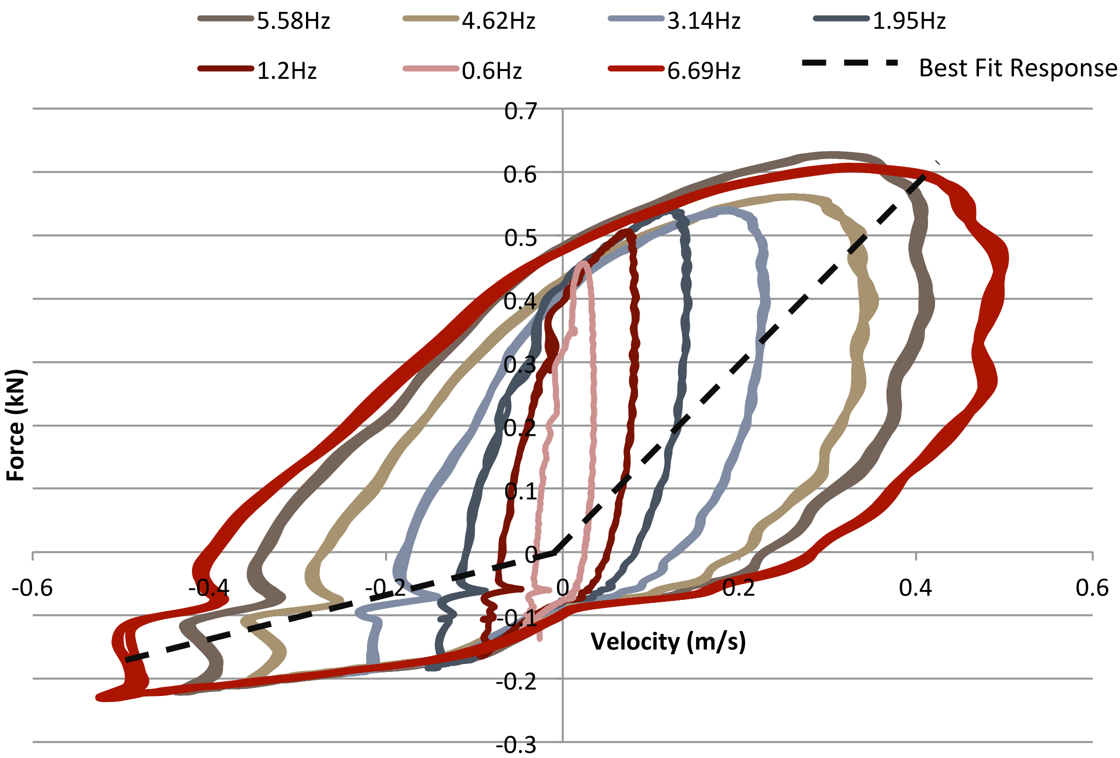


Figure 4-6: Alko Damper Characteristics

From Figure 4-5, it is apparent that the shock absorber exhibits damping characteristics that are closer to that of a ‘normal’ damper and the response is a lot nearer to the ‘best fit’ lines than the Alko shock absorber, Figure 4-6. Given the damper is 30 years old its performance is likely to have reduced compared to its original design characteristics.

Bump Rate:

$$c_b = \frac{F_b}{v_b}$$

$$= \frac{163}{0.53}$$

$$= 307Ns/m$$

Rebound Rate:

$$c_r = \frac{F_r}{v_r}$$

$$= \frac{532}{0.51}$$

$$= 1043Ns/m$$

4.2.4 Natural frequency and Damping Ratios

4.2.4.1 Natural Frequency

$$\varpi_0 = \sqrt{\frac{k_w}{m}}$$

$$= \sqrt{\frac{59{,}000}{350}}$$

$$= 12.98rads^{-1}$$

$$= 2Hz$$

This value is above the typical design natural frequency of a standard road car (1.5Hz) [17] and indicates that the coil spring is stiffer than expected and may result in a harsher ride.

4.2.4.2 Damping Ratios

Bump

$$\xi_b = \frac{c_b}{2m\varpi_0}$$

$$= \frac{307}{9086}$$

$$= 0.03$$

Rebound

$$\xi_r = \frac{c_r}{2m\varpi_0}$$

$$= \frac{1043}{9086}$$

$$= 0.11$$

This values result in an average damping ratio of 0.07, which is considerably below the typical value for a standard road car (0.20-0.25 [17]) but somewhat higher than the Alko damper.

4.3 Road Testing

Previous testing at the Millbrook proving ground indicated that the caravan chassis was subjected to the most stress when travelling over a pothole as discussed in chapter 3.

An identical pothole to that used at Millbrook proving ground was constructed at the Bailey factory and the test procedure as outlined in chapter 3 was repeated using the Sprite caravan. This provided a comparison between the performance of the Alko system, as used on the majority of modern caravans, and the damped coil spring system as used on the older caravan. The test was conducted using the same pothole dimensions and vehicle speeds as at Millbrook as outlined below in Figure 4-7.

For reference, the maximum bump displacement of the hub with the Alko system was 18mm (Bailey Unicorn Valencia) as shown in Figure 4-8.

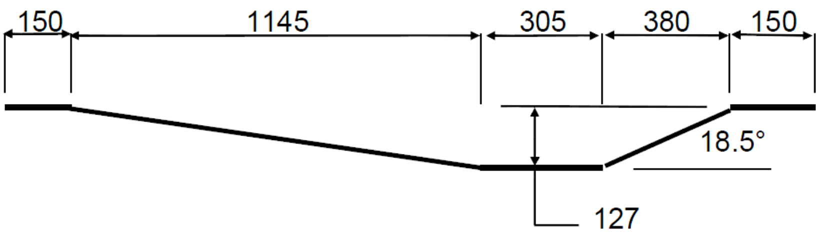


Figure 4-7: Pothole Dimensions

4.3.1 Coil Spring Pot Hole Results

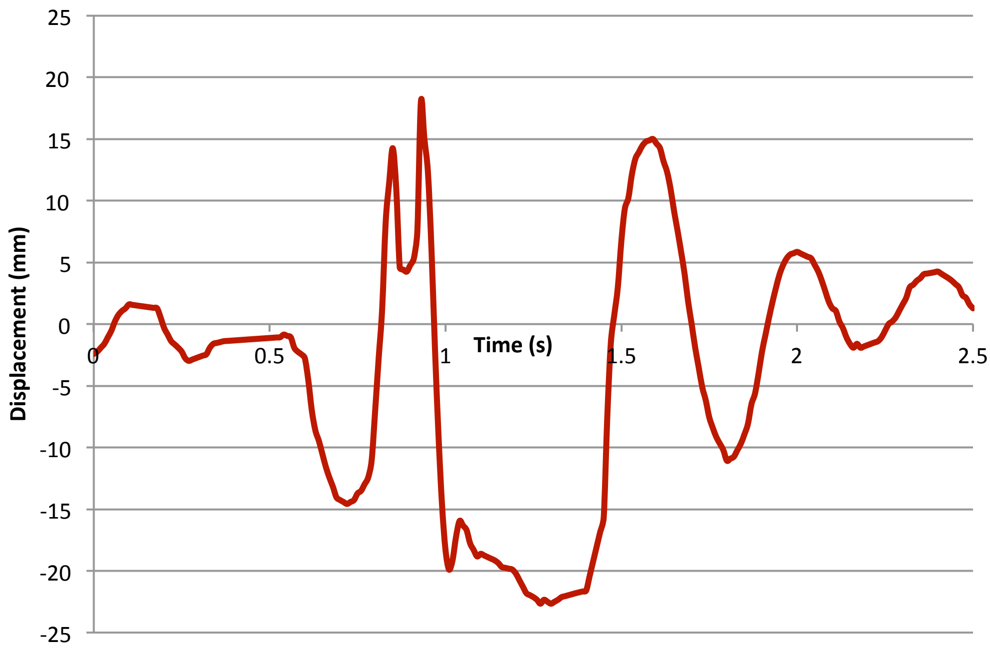


Figure 4-8: Alko Hub Displacement through Millbrook Pothole

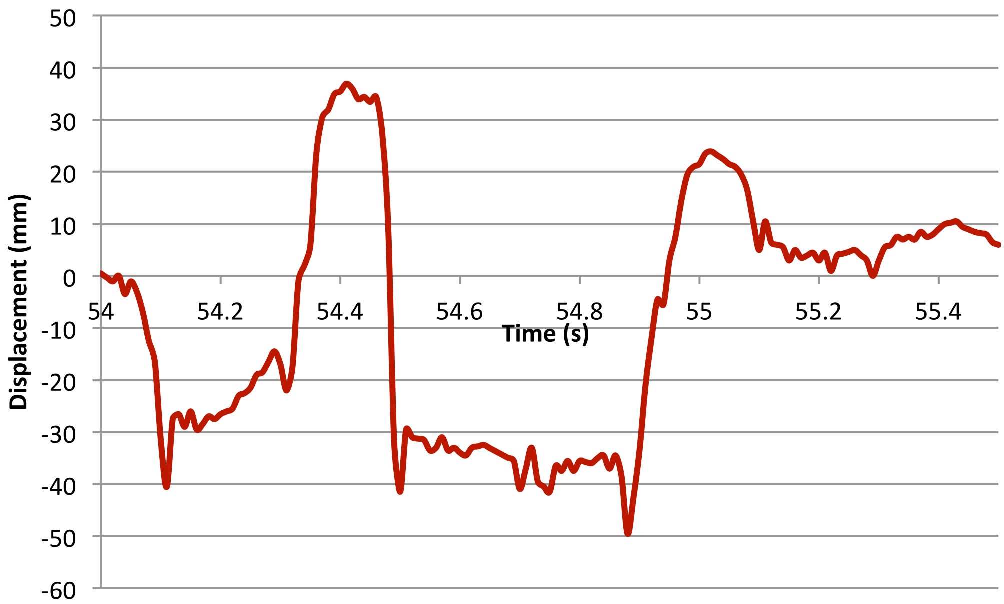


Figure 4-9: Sprite Hub Displacement through Bailey Pothole

Figure 4-9 shows that the maximum displacement of the wheel hub as the caravan travelled over the pothole were 36mm in bump (spring compressed) and 50mm in rebound (spring extended)

4.4 CONCLUSION

The results have indicated that the damped coil spring suspension system, as used in the Sprite caravan, is better suited to handling severe road conditions than the modern Alko system. Although the caravans were different masses, the comparison between the various suspension design parameters (spring rate, damping ratio, travel) indicates that the coil spring system has been better optimised for road use.

The testing conducted on the damper rig shows that the Sprite's shock absorbers are closer to that of a 'normal' car damper and also have damping ratios closer to that of a standard road car when compared to the Alko system. This value, however, can be increased further to achieve better damping performance. The wheel rate of the coil spring system resulted in a natural frequency that is higher than would be expected for a road vehicle. Despite this, the pothole testing indicated that the coil spring system exhibited significantly more compliance and suspension travel than the Alko system. The results do however suggest that the suspension force transmitted to the chassis is similar to that of the Alko system. This may suggest that the coil spring stiffness is too high for the mass of the caravan and this conclusion is supported by the fact that the natural frequency of the mass-spring system is higher than expected when compared with a standard road car. Furthermore the high suspension force may be attributed to the fact that the size and weights of the wheels are smaller than the wheels used on the Alko system whereas the pothole dimension is the same. Smaller wheels transfer more energy when travelling over bumps in the road and ideally the test should be repeated with the same weight and diameter wheels. The absolute force transmitted to the Sprite caravan (weight + suspension force) is however, substantially less than that exhibited on the caravan with the Alko system.

4.5 Next Steps

A trailing arm, damped coil spring suspension should be developed into a prototype for further testing. The spring and damper rates (based on the Unicorn Valencia) should have the following values.

- A maximum caravan natural frequency of 1.5Hz resulting in a wheel rate of 58.7kN/m (Spring rate of around 70kN/m)
- A minimum damping ratio of 0.18 resulting in an average damping rate of 1635 Ns/m
- Minimum wheel total travel of 80mm.

The following chapter investigates how a caravan chassis system could be optimised to develop a new lightweight and stiff structure. There is a focus on the use of sandwich panel structures as these are proven to be lightweight and strong but they are also commonly used within the caravan industry already. The investigation begins with an analysis of the loading through the present chassis, which then, along with previous data, contributes to the development of a new chassis and suspension system design specification.

5 : Design Optimisation of a Caravan Chassis

5.1 Introduction

This chapter moves on from investigating the current state-of-the-art product and postulates a new design approach to address the issues highlighted in chapter 2. As discussed in chapter 4, the trailing arm, damped coil spring suspension system was thought to be the most suitable for the prototype and as such this chapter primarily focuses on the design and development of a chassis matched to this suspension arrangement.

The investigation begins by looking at the loading regime on a typical caravan and develops an optimised chassis system using finite element methods. The ideation phase follows this analysis and several chassis concepts are presented.

5.2 Optimisation

5.2.1 Loading Regime

Figure 5-1 below outlines the loading condition on the chassis when in transit and when sited by the user.

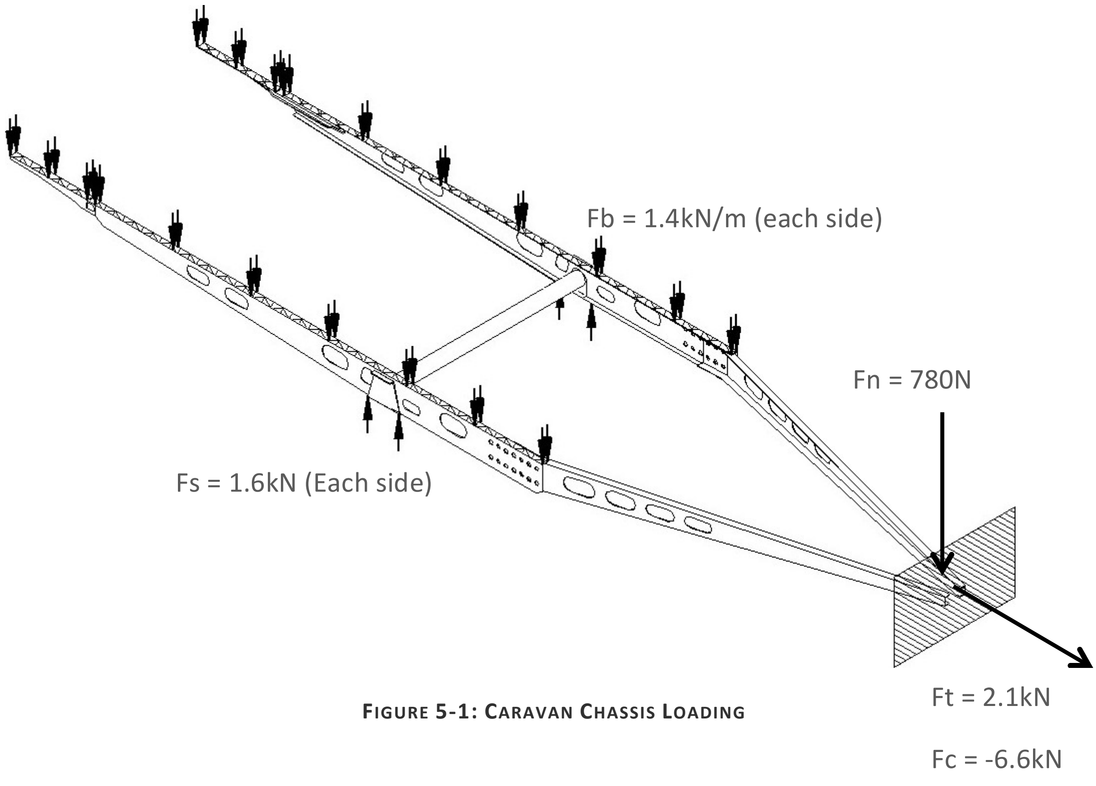


Figure 5-1: Caravan Chassis Loading

The maximum wind loading on the caravan side is approximately 312N/m^{2}.

The maximum area of the caravan side is 10m^2

Load	Value	Description
Fb	*1.4kN/m*	*Distributed load from caravan body and contents acting over the chassis length on each side. Typical length chassis is approx. 4.5m*
Fs	*3.6kN*	*Maximum load imparted on the chassis from the suspension system. Impact load in worst conditions (deep pothole)*
Fn	*780N*	*Nose weight acting vertically up on the ball hitch*
Ft	*2.1kN*	*Maximum hitch load when accelerating to 50mph*
Fc	*-6.6kN*	*Maximum hitch load with car decelerating from 50mph to stop*

TABLE 5-1: LOADS ON CARAVAN

5.2.2 TOPOLOGY OPTIMISATION

Topology optimisation is an engineering technique used to determine the best arrangement of material within the specified design space. The common formulation of topology optimisation is to minimise the overall strain energy of the structure while fulfilling a constraint on the maximum volume of material available. [18]

In this investigation the optimal structure to support the applied mechanical loads was created using the Solid Isotropic Microstructure with Penalisation (SIMP) method of topology optimisation [19]. The SIMP method defines the optimal structure by varying the apparent density of the material in the models finite elements according to the sensitivity value of each element. In this model the strain energy density was used for the sensitivity. Elements with a higher sensitivity value are considered significant to the structure and thus have their apparent density increased (or maintained at the maximum), while elements with low strain energy density are considered unimportant and have their apparent density reduced. The SIMP model assumes the following relationship between the apparent density of an element and it's material properties.

$$K_0 = x_e{}^p$$

Where K_0 is the stiffness of a full element and xe is the element apparent density and p is the penalization power. Penalization is used to control the kind of structure the model converges to. A low p value (e.g. p = 1) results in a structure made up of elements with different apparent densities, while a higher value (p = 3) results in a discrete solution with elements possessing either maximum apparent density or no material [20]. In the caravan model p = 1 was used. This was chosen as the apparent density ratio (x_e) can be used to represent the thickness of the plate at each element.

This can be represented as the optimality function displayed below.

Minimise: $$\sum_{e=1}^{N} (x_e)^p \mathbf{u}_e^T \mathbf{k}_0 \mathbf{u}_e$$

Subject to: $$V(x) \leq V_{max(x)} \qquad V(x) \leq V_0$$

Where: $$0 < x_{min} \leq x \leq 1$$

Where $\mathbf{u}_e$ and $\mathbf{k}_0$ are the element displacement vector and stiffness matrix respectively, x is the apparent density ratio, x_{min} is the minimum density; usually 0.001 to avoid singularity. However a value of 0.5 was used as apparent density represents thickness, this would be considered the minimum thickness of the caravan floor. p is the penalization power, V(x) and V_0 are the current design volume and target volume, respectively. There are several methods available to solve the optimality criteria, but this method uses Sigmund's 99-line method [21].

5.2.3 Results

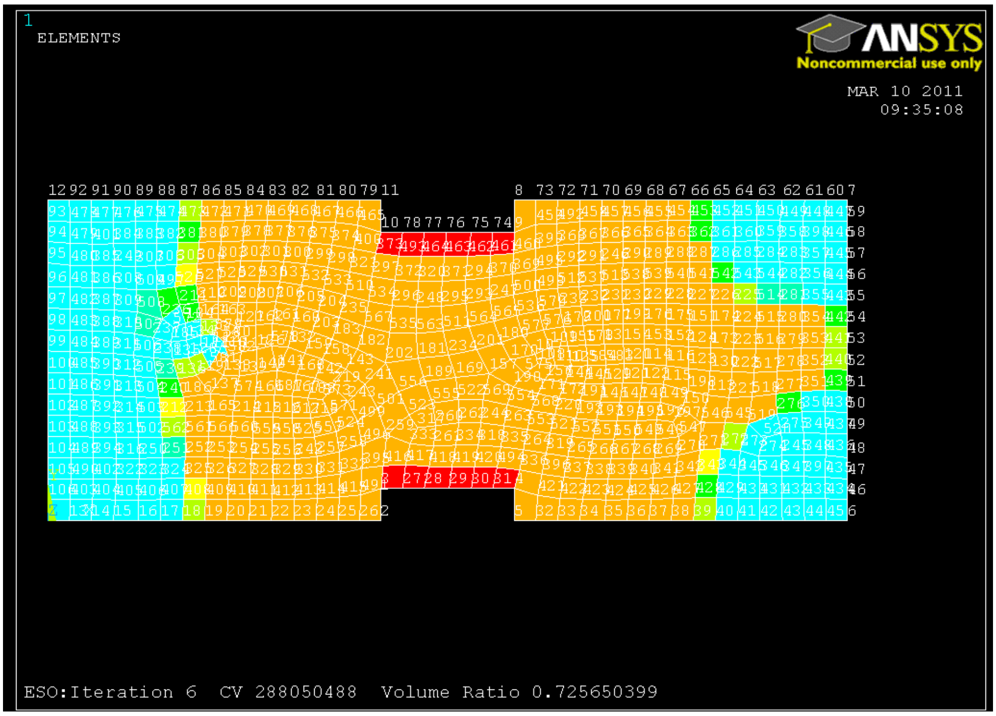


Figure 5-2: Topology Optimisation Results

5.2.4 Conclusion

Although this method is not absolutely representative in all towing conditions it provides a good indication of the way a caravan floor would need to be designed if required to be the sole load bearing structure. The optimisation results indicate that, when the caravan is on tow, the stress distribution on the floor is predominantly down the centre and surrounding the wheel cut-outs. This in turn suggests that the relative material thickness should be greater in these areas to compensate for the high stress factors. It was therefore concluded that the design of the chassis and floor should ensure that there is sufficient support in these areas.

5.3 Design Specification

This design specification was developed based on the broad requirements outlined in chapters 1 to 4 and also considers the broader issues of cost, manufacturing and mass production.

5.3.1 Performance

- The system must be compatible with the current range of Bailey caravans and the Alu-Tech construction methods.
- The system must be able to withstand the loading outlined in 5.2.1
- The system must be at least 40kg lighter than the current equivalent chassis based on the design of the Bailey Unicorn Valencia caravan.
- The system must reduce the transmission of vibration (acceleration amplitude) through the suspension system by a factor of at least 2.
- The suspension must have bounce travel of at least 60mm and rebound travel of at least 30mm
- The system should be designed around a ride frequency of approximately 1.5Hz
- The prototype system should have a wheel rate of approximately 60-70kN/m (based on the Valencia model)
- The system should exhibit an average damping ratio of around 0.18.
- The system should be compatible with mainstream anti-snaking devices.
- The system must not contain any timber or other organic materials.
- The system must be compatible with a standard tow bar and 12pin electrical system.
- The system should be able to be applied to a range of caravan sizes (widths and lengths vary from 2.5m to 8m)
- The suspension system should be easily maintained with household tools
- The system should have a target life of 15years based on 2,000 miles pa.
- The system must be able to withstand temperatures from -20°C to +50°C.
- The suspension system should have a degree of camber and toe control
- The ride height of the caravan floor must be less than 600mm

5.3.2 Manufacturing

- The system must be able to be made in no more than 6 stages of 11minute cycles.
- The system must be compatible with the current plant at the Bailey factory (Appendix III)
- The system should use materials and methods that are available to Bailey or are accessible at reasonable cost.
- The manufacturing method must not compromise the design of the rest of the caravan structure or its interior.
- The system should be modular so it can be easily shipped to other manufacturers if necessary. Ideally at least 25 units per articulated lorry.

5.3.3 Cost

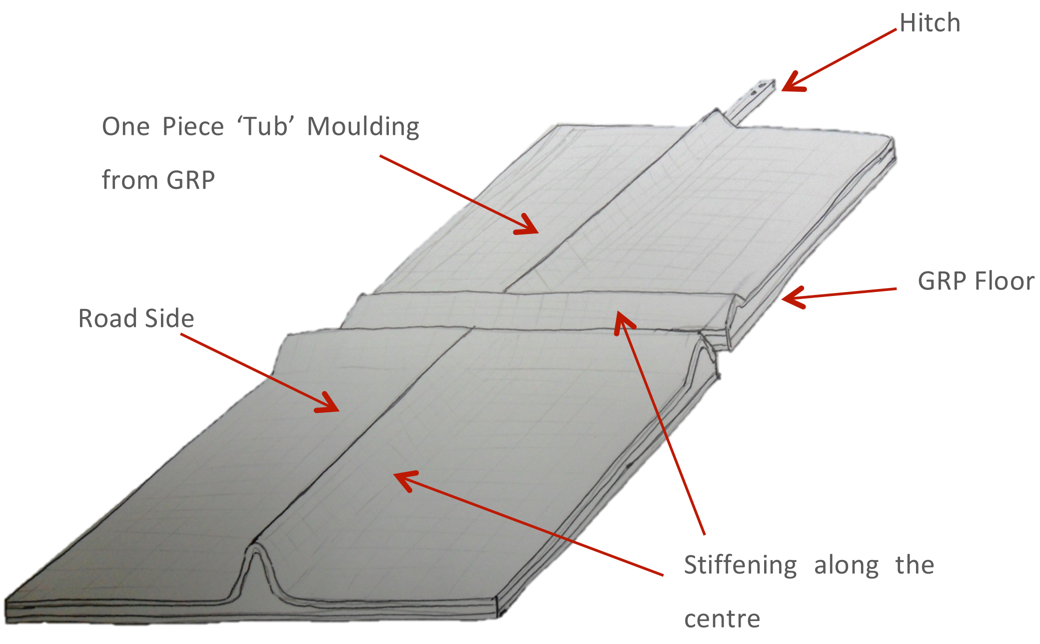
- The system should cost less then £1,150 (including the floor) based on the production of 8,000 units pa.
- The prototype should cost less than £10,000 per iteration (not including body shell and furniture).
- The cost of annual maintenance should be in line with the present expected cost (<£500 pa)

5.4 Design Concepts

The three concepts below were selected as the three most suitable ideas based on the initial brainstorming process.

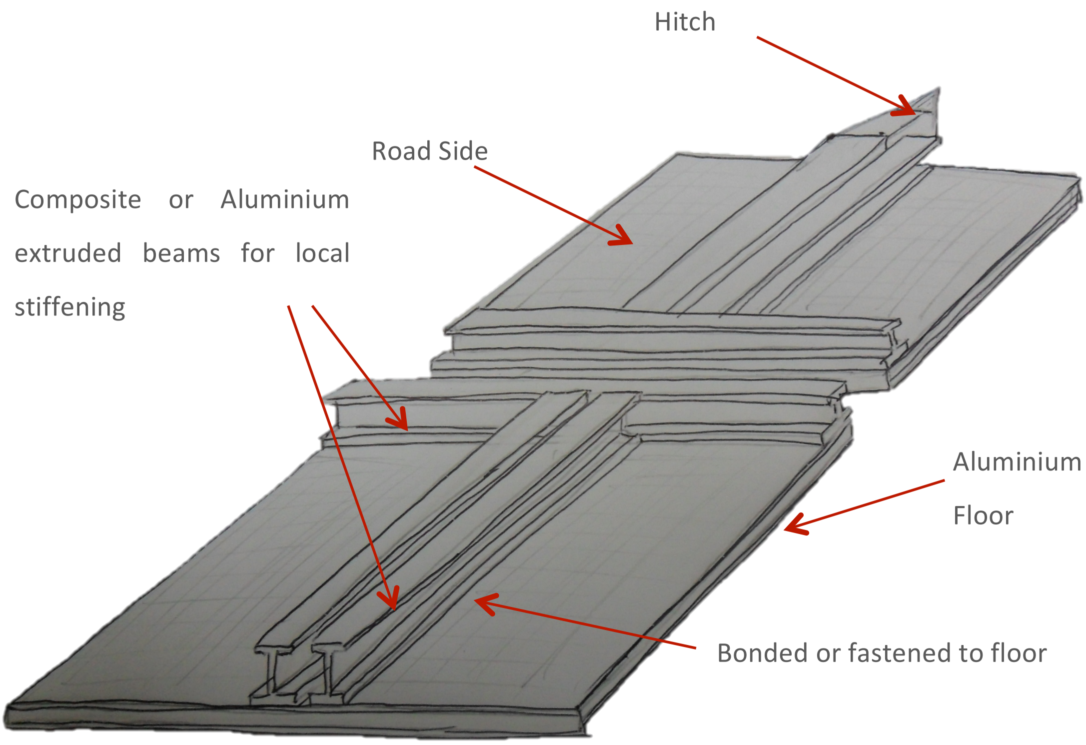
5.4.1 Concept 1

Single 'Tub' Moulding with localised stiffening



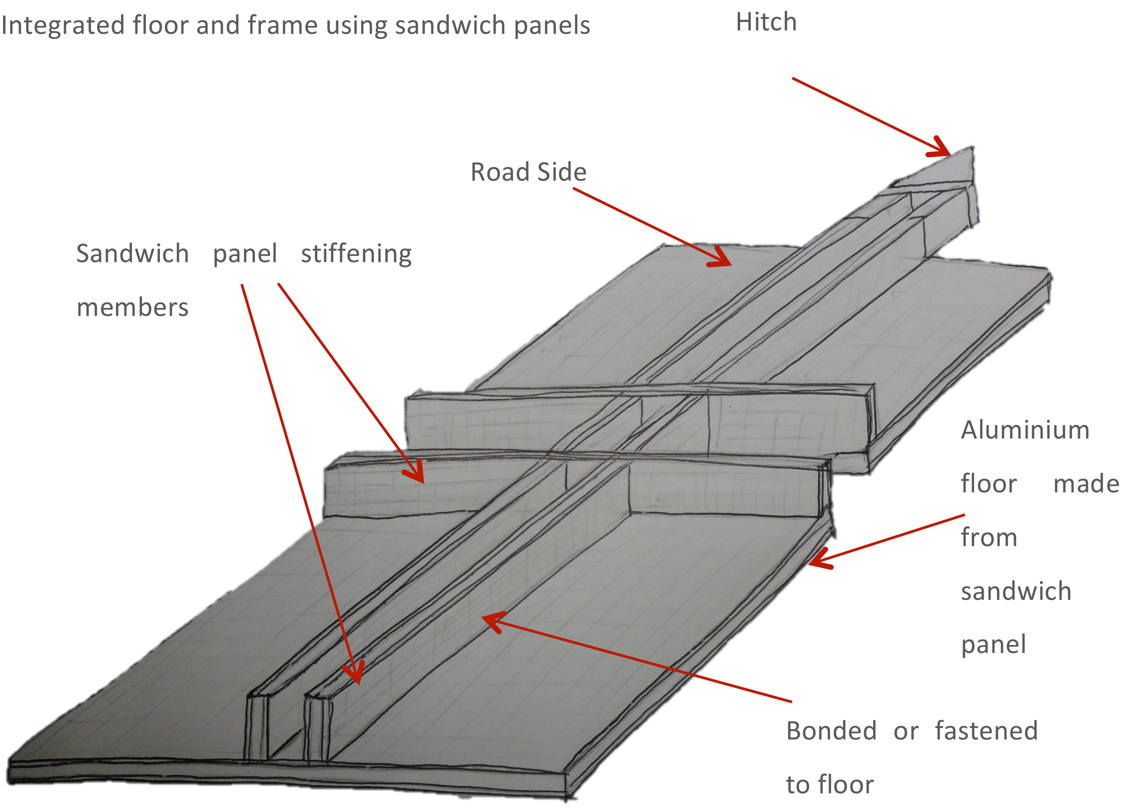
5.4.2 Concept 2

Floor on frame system using extruded beams for stiffening



5.4.3 Concept 3

Integrated floor and frame using sandwich panels



5.4.4 Concept Analysis

The following review process uses a concept-scoring matrix [22] to select the best option from the 3 concepts.

Concept	*Weight Saving Potential (0.25)*	*Ease of Manufacture (0.1)*	*Cost (0.1)*	*Weather Proofing (0.1)*	*Maintenance (0.1)*	*Strength (0.2)*	*Compatibility (0.15)*	*Eco Impact (0.1)*	*Total*
1	*4*	*1*	*1*	*4*	*3*	*4*	*4*	*2*	***3.2***
2	*2*	*4*	*2*	*3*	*3*	*4*	*4*	*2*	***3.3***
3	*3*	*3*	*4*	*2*	*3*	*3*	*4*	*3*	***3.45***

Table 5-2: Concept Scoring Matrix

5.4.5 Conclusion

The conclusions below were drawn based on the concept scoring matrix, Table 5-2.

Concept 1 would be an ideal design if the cost of the system were not taken into consideration. It is likely that this would produce a highly optimised, stiff and lightweight structure that would be extremely weather proof. This type of system may become more feasible when composite layup manufacturing processes become more developed.

Concept 2 is again a viable solution but is likely to be limiting to design flexibility, bulky and heavy. The nature of extruded profiles means that they cannot be easily optimised for light weighting. Moreover the cost of manufacturing an extruded composite profile may prove to be too great at this stage.

It was concluded that concept 3 would be the most feasible system to manufacture and offered the highest amount of design flexibility. The configuration would be inexpensive to manufacture, compared to the other concepts, and the processes used for such manufacturing are readily available at the Bailey factory. Sandwich panel technology is commonly used in caravan production as it is proven to be both strong and lightweight. Moreover the use of sandwich panel systems in other areas of industry, including automotive, has been proven to be a cost effective way of developing a stiff lightweight structure. The panels can be accurately cut using CNC processes and can be easily modified to suit a range of caravan sizes and weights. The investigation into the choice of the sandwich panel configuration was critical to ensuring the structural integrity of the chassis.

5.5 Sandwich Panel Analysis

Sandwich panel structures represent a key component of composite structural design technology. They provide structural efficiency of very lightweight materials 'sandwiched' between higher performance (strength, stiffness) composite laminates in order to carry tension, compression and shear loads imposed upon the resultant structure [23]. They were originally developed for construction purposes and are now commonly used in a wide range of applications including the automotive and aerospace industries. The design intention is to develop an integrated chassis and floor system made entirely from sandwich panels utilising their high strength and lightweight material properties.

This study investigates the mechanical properties of four different sandwich panel configurations that could be used in the development of a new integrated caravan chassis and floor. Specifically, the investigation analyses the panels' stiffness, compressive strength and impact resistance. It was the intention that the findings of this chapter were used to influence the choice of materials for the development of the first full-scale prototype. The chapter's conclusion also accounts for cost and manufacturing considerations.

The sandwich panel configurations investigated in this study are outlined below.

Name	***Skin Material***	***Core Material***	***Skin (mm)***	***Core (mm)***	***Net (mm)***	***Mass/m^2 (kg)***
Original Floor	*Plywood*	*Styrofoam*	*4.5*	*34.5*	*43.5*	*6.79*
Aluminium Floor	*Aluminium Alloy (3003)*	*High Density (HD) Polystyrene*	*0.8*	*40*	*41.6*	*10.18*
GRP Floor	*GRP (Chopped strand)*	*HD Polystyrene*	*1.2*	*40*	*42.4*	*7.50*
Kemlite	*Heavy Duty GRP (Cross Woven)*	*Low density Foam & Resin Struts*	*2.5*	*42*	*47*	*16.61*

Table 5-3: Panel Configurations

5.5.1 Three Point Bending Tests

In order to provide an indication of the panels' stiffness a simple 3-point bending test setup was devised using a 700x80mm beam of each of the four configurations shown in Table 5-3.

Each specimen was placed in an Instron loading machine in the arrangements shown in Figure 5-3 and Figure 5-4 below. A force was applied to the centre of the beam at a deflection rate of 10mm/minute; the deflection was measured up to the point of failure. Figure 5-3 shows the force being applied perpendicular to the skin of the panel (through plane) whereas Figure 5-4 shows the force being applied to the side of the panel (in plane).

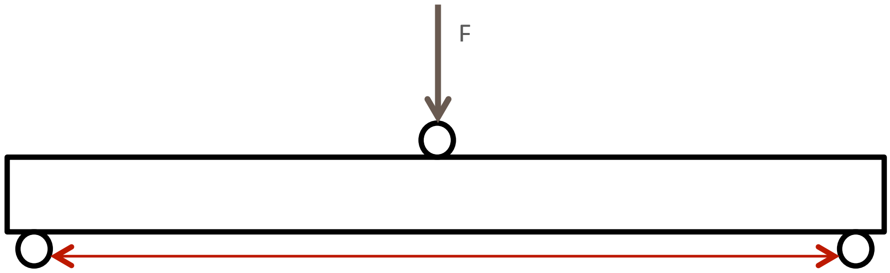


FIGURE 5-3: 3 POINT BENDING LOADING IN PLANE WITH SKIN

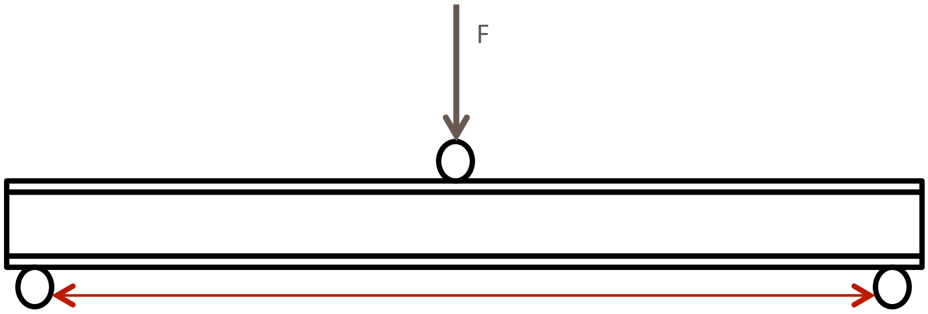


FIGURE 5-4: 3 POINT BENDING LOADING THROUGH SKIN PLANE

5.5.1.1 RESULTS

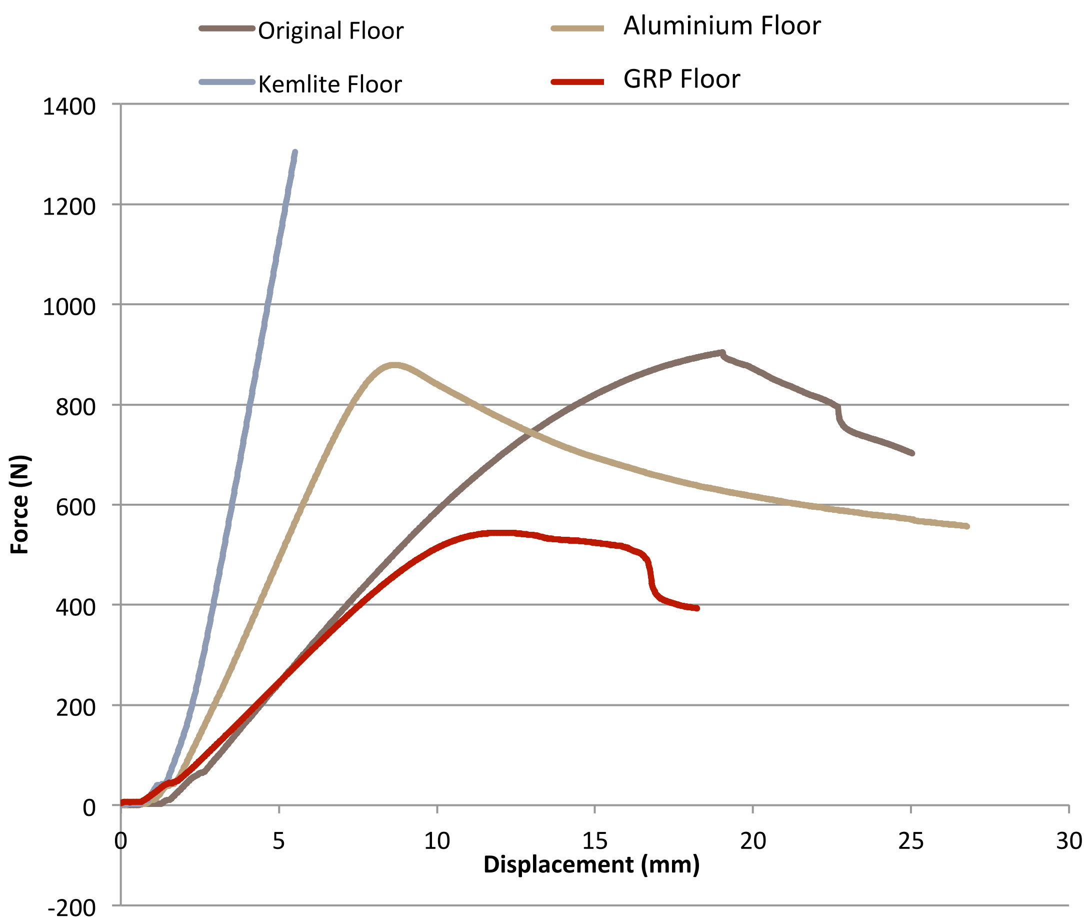


FIGURE 5-5: 3 POINT BENDING RESULTS (THROUGH PLANE)

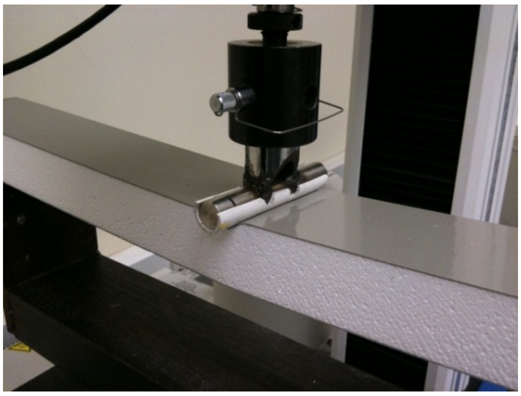


Figure 5-6: GRP Beam

GRP: Figure 5-6

The GRP and HD Polystyrene panel had low beam stiffness, similar to that of the ply-Styrofoam panel. The panel failed as the foam began to compress under the load and plastically deformed the GRP skin. As with the ply panel it is unlikely to be loaded this way in reality and therefore its stiffness can be attributed to the first section of the curve shown in **Figure 5-5**.

Beam Stiffness: 61kN/m

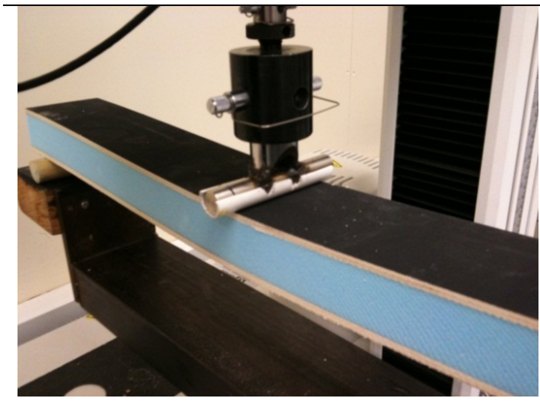


Figure 5-7: Ply Beam

Original Floor: Figure 5-7

The panel failed when the plywood began to crack and delaminate from the Styrofoam core. The nature of the loading resulted in a very localised force being imparted on the beam that caused it to fail in this way. In reality it is likely that the beam stiffness under normal loading conditions will be similar to the beginning of the Force vs. Displacement curve, Figure 5-5.

Beam Stiffness: 70kN/m

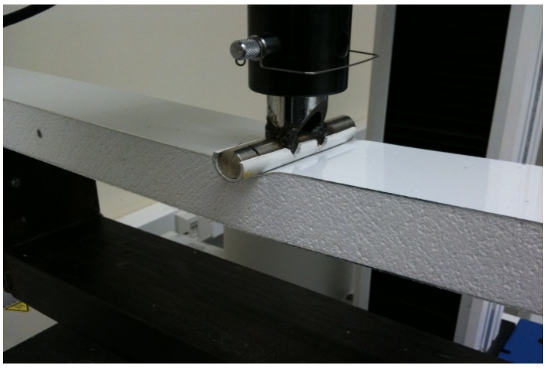


Figure 5-8: Aluminium Beam

Aluminium: Figure 5-8

As with the GRP panel the aluminium sandwich deformed plastically under high loading. Despite this the beam showed high overall stiffness in the first stages of loading as shown in Figure 5-5.

Beam Stiffness: 136.8kN/m

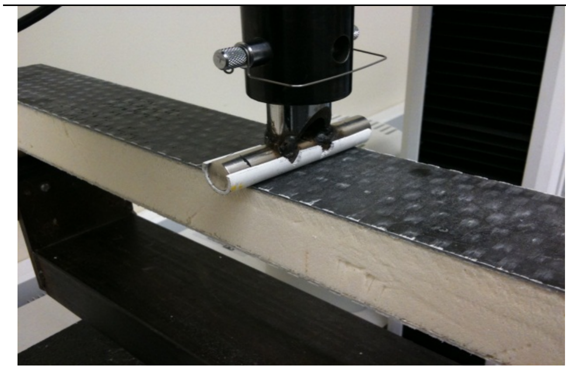


Figure 5-9: Heavy Duty GRP Beam

Heavy Duty GRP (Kemlite): Figure 5-9

The heavy duty GRP sandwich panel exhibited very high stiffness and failed at around a load of 4kN. It is likely that the fibre-resin matrix failed due to crack propagation through its thickness.

Beam Stiffness: 336.2kN/m

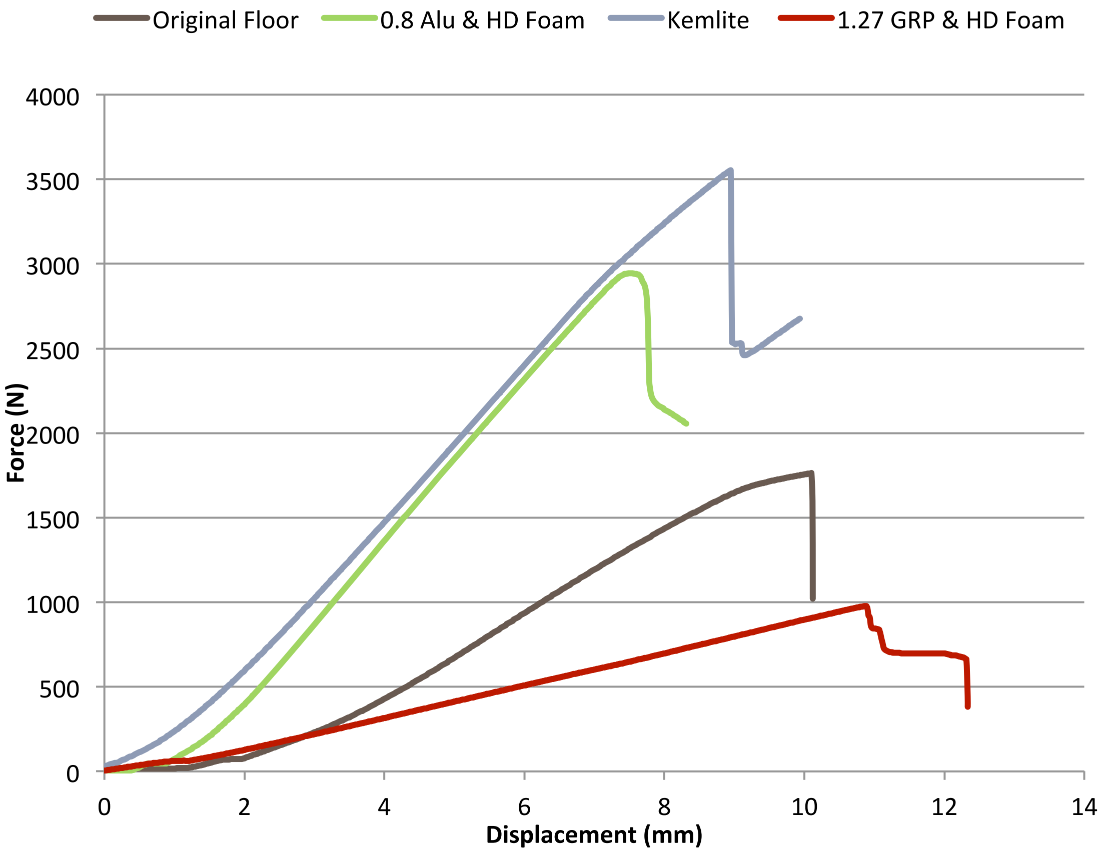


Figure 5-10: 3 Point Bending (In Plane)

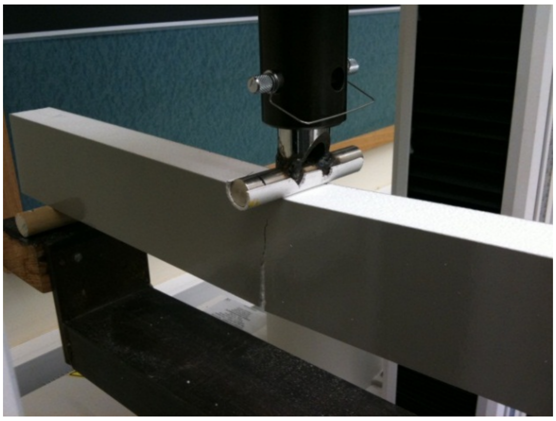


Figure 5-11: GRP Beam

GRP: Figure 5-11

The GRP beam failed due to the propagation of a crack through both the skin and the core material indicating that the tensile strength of the skin was too low to withstand the stress.

Beam Stiffness: 95kN/m

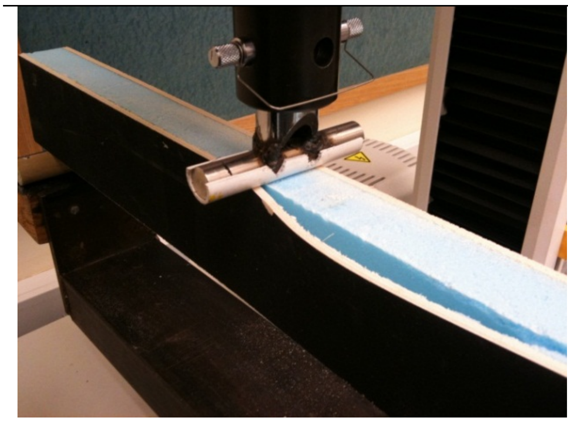


Figure 5-12: Ply Beam

Original Floor: Figure 5-12

The panel failed due to the delamination of the ply from the core material indicating that the bond strength was too low.

Beam Stiffness: 247kN/m

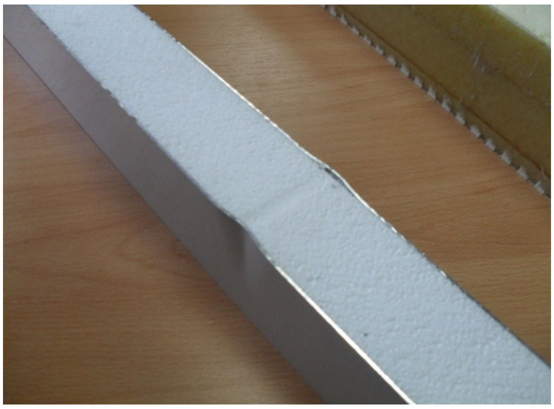


Figure 5-13: Aluminium Beam

Aluminium: Figure 5-13
The aluminium beam had high stiffness in this orientation and failed due to partial delamination and plastic deformation of the skin and core material.

Beam Stiffness: 472kN/m

Figure 5-14: Heavy Duty GRP Beam

Heavy Duty GRP (Kemlite): Figure 5-14
The panel exhibited a similar stiffness to the aluminium panel and failed due to the delamination of the GRP skin from the core material.

Beam Stiffness: 429kN/m

5.5.2 Compressions Tests

5.5.2.1 Method

The test was conducted using the guidelines of BS EN826: Thermal insulating products for building applications: Determination of compression behaviour. A 100x100mm specimen was subjected to a compression rate of 10mm/min using the setup as shown in Figure 5-15 below. The force and displacement were recorded.

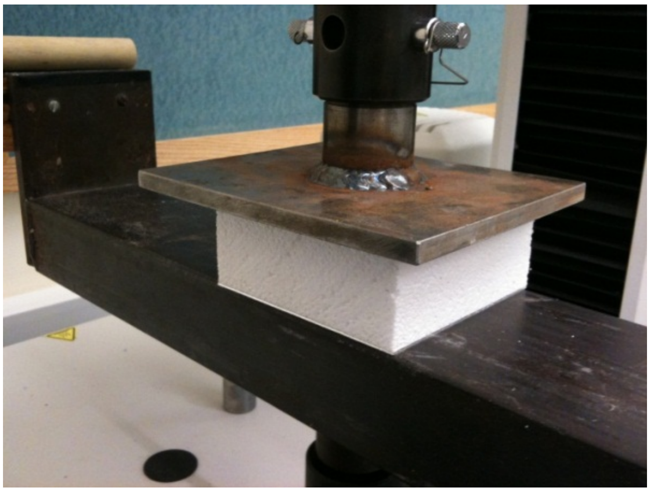


Figure 5-15: Compression Testing

5.5.2.2 Results

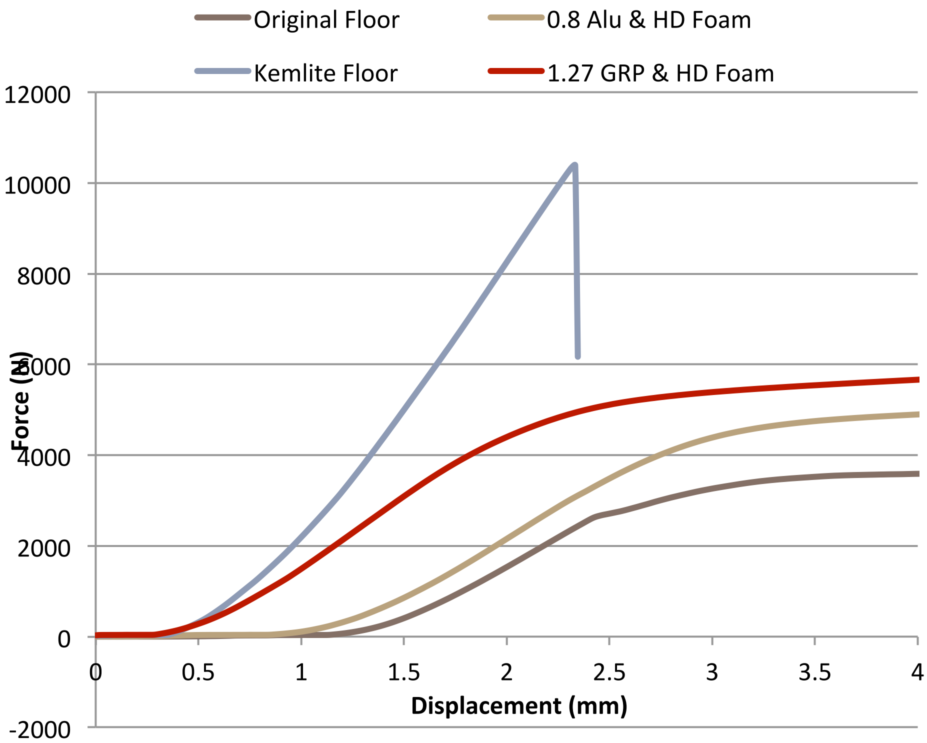


Figure 5-16: Compression Loading Results

5.5.2.3 Discussion

Figure 5-16 shows that the panels with the HD foam cores have a similar compressive stiffness indicating that the facing skin has little effect. The Styrofoam core does not perform as well due to its lower density. The heavy duty GRP core has a very high compressive stiffness due to the resin struts that run the length of the section. The panel is shown to fail when the struts reach their compressive limit and buckle.

5.5.3 Point Force Tests

This set of tests was intended to investigate the qualities of the panels as a floor material. A caravan floor needs to be suitable for a range of different habitation activities and as such has to be resistant to impact from falling objects and point loads. Although the surface of the sandwich panel is unlikely to be exposed it is important that it is able to resist indentation to ensure that the flooring laminate retains a good surface finish.

5.5.3.1 Method

Figure 5-17 and Figure 5-18 below outline the two different tests used to analyse the impact resistance of each of the panels. Figure 5-17 is a schematic of the drop test conducted to evaluate the resistance of the panel to a high impact force. A mould of the impact hole was taken and its dimensions recorded. Figure 5-18 shows the panel being subjected to a localised point force at a compression rate of 2mm/min.

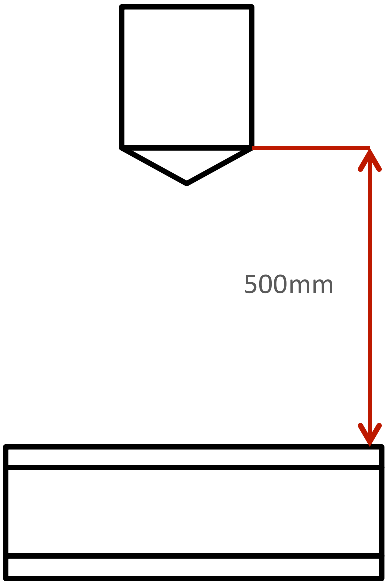


Figure 5-17: Drop Test

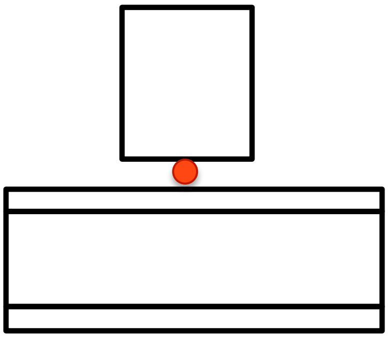


Figure 5-18: Point Load Test

5.6 Results

Material	*Depth of Indentation (mm)*	*Diameter of Indentation (mm)*
Ply (Original Floor)	*7*	*20*
0.8 Aluminium & HD Foam	*5*	*15*
1.27 GRP & HD Foam	*3.5*	*25*
Kemlite	*Negligible*	*Negligible*

Table 5-4: Drop Test Results

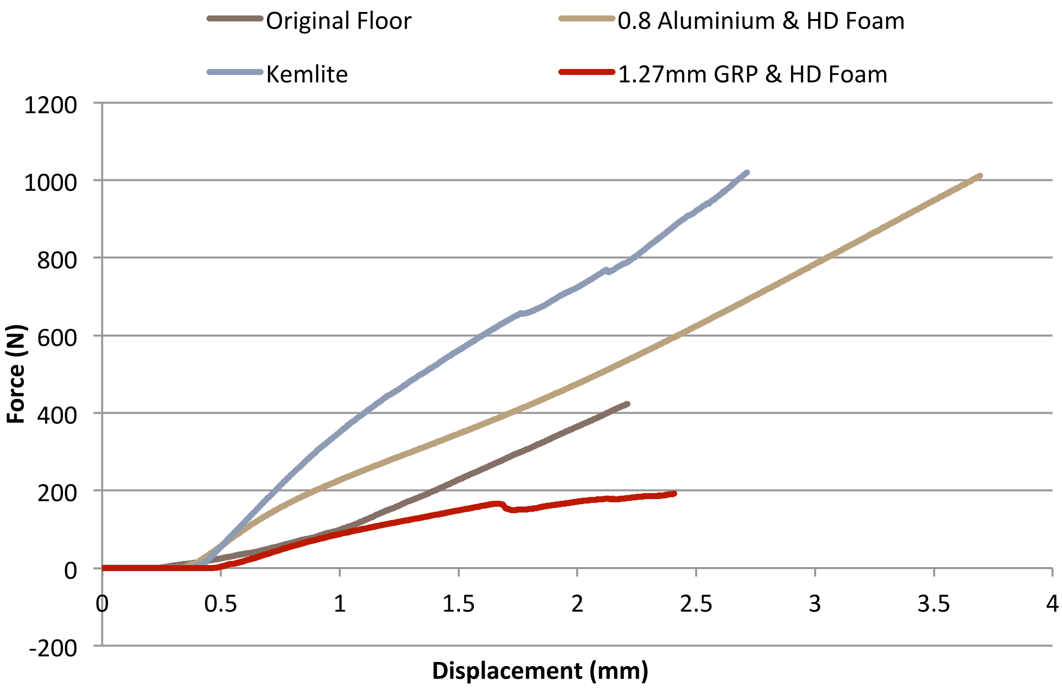


Figure 5-19: Point Load Results

5.6.1 Discussion

The results from the drop test, Table 5-4, indicate that the GRP disperses the impact energy more widely through the material resulting in a shallower indentation over a larger area. Furthermore the results show that the aluminium deforms plastically on impact and consequently has a deeper indentation although over a smaller area. The plywood has the worst characteristics for impact resistance with a large indentation over a large area. The heavy duty GRP had minimal damage to its surface and resisted impact extremely well.

The results from the point loading test, Figure 5-19, show that the GRP is least resistant to a localised force but doses deform elastically up until a threshold of around 190N, approximately equating to a stress level of 7.5MPa. Both the aluminium and ply deform plastically but the aluminium has significantly higher stiffness and resistance in the first stage of loading shown by the steeper gradient in Figure 5-19. The heavy duty GRP floor has very high resistance and only fails due to crack propagation through the surface.

5.6.2 Conclusion

The results indicate that the heavy duty GRP panel exhibits the highest stiffness properties and greatest impact resistance of the different sandwich configurations. However, as outlined in chapter 2 the panel is significantly heavier than the other configurations that could result in an excessively heavy overall structure. Moreover separate testing has indicated that the panel does not support bolted joints very well and the skin is unable to retain a bolt without failing. Furthermore the manufacturing process required to make the panel is lengthy and may not stand up to the demand of the present rate of production. The process is also significantly more expensive than other methods due to the injection of the resin struts through the laminate core resulting in a net cost of around £70/m^2. Moreover any machining that is required to produce cut-outs for wheels, pipes, holes and ventilation produces a large amount of glass fibre dust which is hazardous to the operator and hard to dispose of safely. It was therefore recommended that this material is not used for the development of the floor and chassis until it has been developed further and is able to be produced more quickly and cheaply than at present.

The lighter duty GRP and Ply panels are very lightweight and are easy to produce safely and cheaply with costs of around £20/m^2 and £17/m^2 respectively. The process for manufacture is common within the industry and similar panels are being used in the sides and ceilings of the caravan body already. Testing has indicated however, that the panels do not possess a high enough stiffness or impact resistance for the development of an integrated floor and chassis. The present plywood floor requires a separate steel chassis to ensure structural integrity and previous testing has indicated that the floor can fail under its own weight without the chassis as discussed in chapter 2. Moreover due to the limitations of plywood manufacture the floor is made from a number of panels rather than one complete sheet that can generate further weak points within the structure.

The aluminium panel provides a good compromise between stiffness, impact resistance, weight, ease of manufacture and cost at approximately £28/m^2. The panel exhibits similar stiffness to the heavy duty GRP panel when loaded in plane and is substantially stiffer than the current ply panel used for the floor. Aluminium sheet is widely available in coils that can span a caravan floor without having to be cut thus ensuring maximum load carrying capabilities. Furthermore the design principle of integrating central struts from the heavy duty GRP sandwich could be used to further increase the through plane bending stiffness as shown in Figure 5-5. It was therefore recommended that the development of the floor and chassis system should incorporate this panel system and this should be validated with further testing once the first prototype had been manufactured.

5.7 Proposed Prototype Design

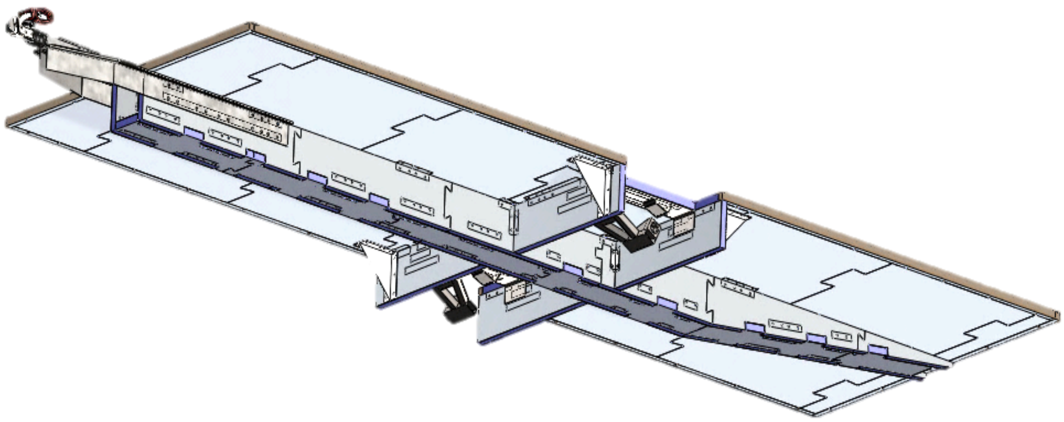


Figure 5-20: Prototype 1

Figure 5-20 shows a 3D CAD model of prototype 1. The structure comprises of a floor fastened to a 'spine' chassis that aims to stiffen the structure in the key areas as dictated by the analysis in chapter 4. The trailing arm suspension sub-frame is bolted to both the floor and lateral spine members in the centre of the chassis. The intention of this system is to move towards a more monocoque structure where the three main structural components (floor, chassis and shell) contribute to the overall stiffness. Both the floor and the 'spine' are made from the aluminium-foam-aluminium sandwich panel deemed to be the most suitable as discussed in chapter 4. A tongue and groove system is used to locate the spine into the floor and also to allow good force distribution throughout the structure. Ideally the spine should be integral to the floor, made from one complete moulding, but the cost implications of this are far too great.

The hitch members are bolted to both the floor and the 'spine' and are designed to fit the Alko hitch coupler.

5.8 FEA Analysis

Based on the findings in the previous section and the conceptualisation process, this study compared the performance of the current caravan chassis design with the prototype model using Finite Element Analysis (FEA) simulations. The aim of the study was to validate the FEA results against 'real life' tests and also to provide a benchmark model so that new prototypes could be improved upon through future design iterations.

5.8.1 Original Chassis and Floor Model

5.8.1.1 Model Simplification

In order to reduce the solving time and the chance of error the original caravan chassis model was simplified by removing holes, cutouts and other complex geometries, Figure 5-21. A simple Ply-Styrofoam-Ply sandwich panel floor was also incorporated into the model.

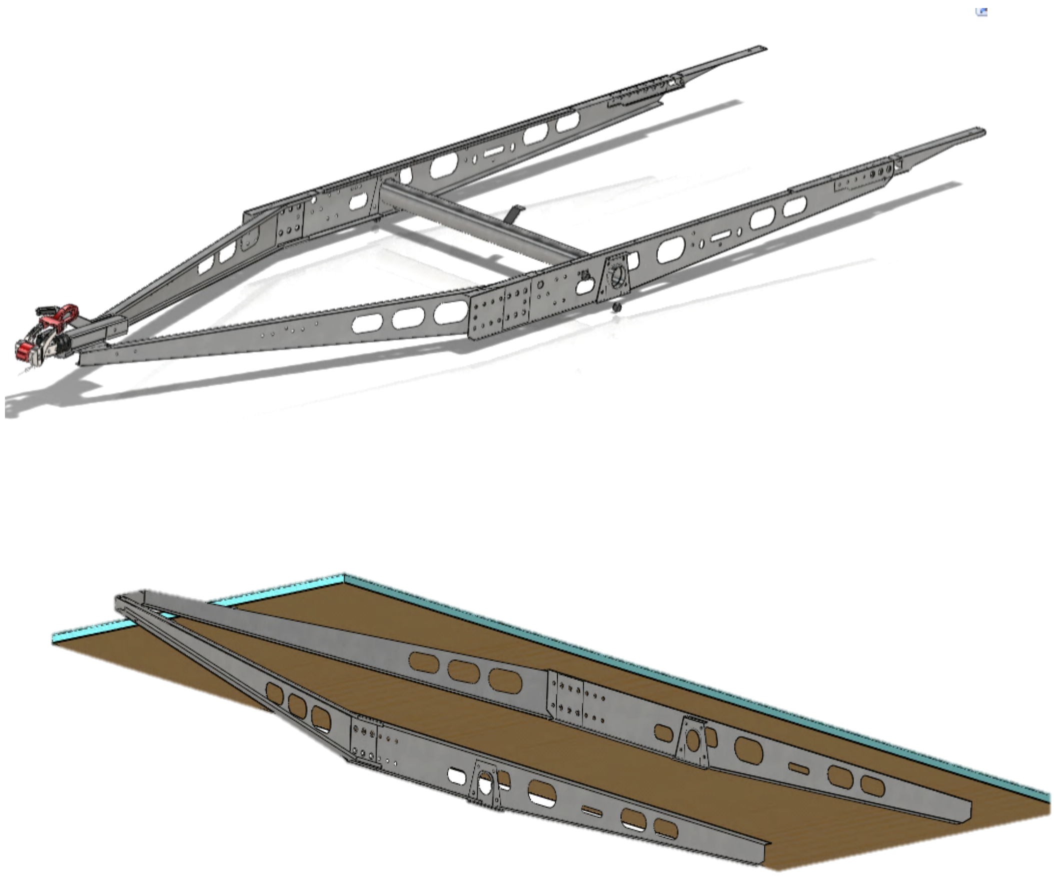


Figure 5-21: Model simplification

5.8.1.2 Loading Conditions

The model was setup to replicate the static loading conditions as outlined in chapter 2. The central suspension axle housing was constrained and the hitch was loaded vertically upwards with a force 1000N as shown in Figure 5-22. The meshing details can be found in Appendix IV.

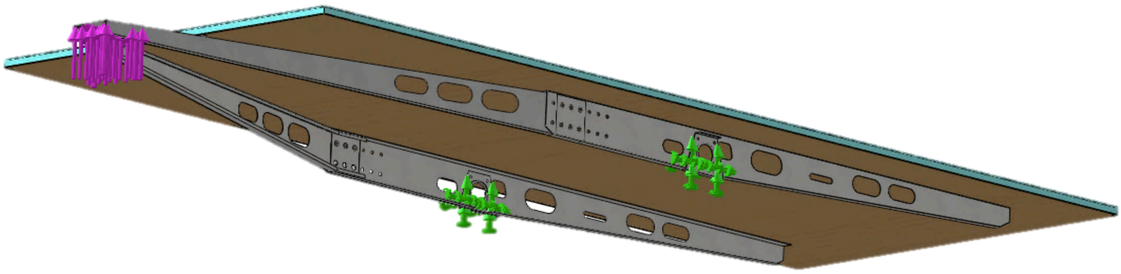


FIGURE 5-22: LOADING ON ORIGINAL CHASSIS

5.8.1.3 Results

The chassis frame alone, Figure 5-23, was loaded at the hitch (1000N) and constrained at the centre suspension mounts. The maximum displacement of the structure was 57mm at the hitch.

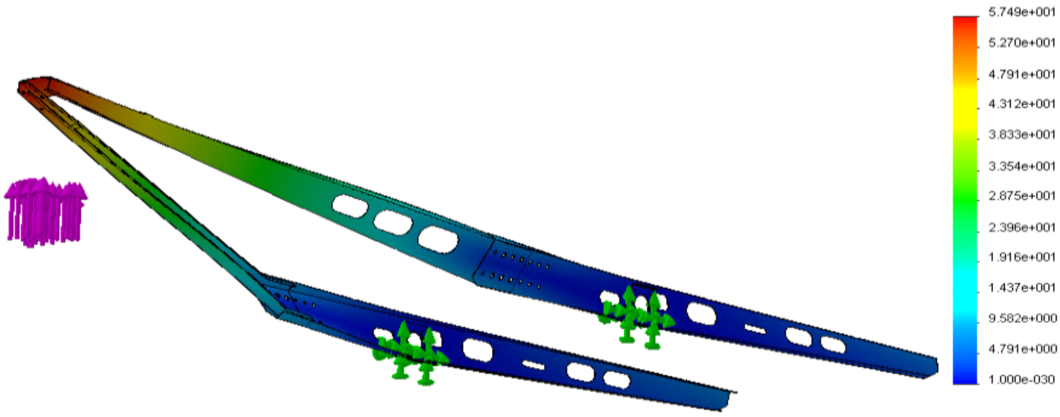


FIGURE 5-23: CHASSIS FRAME DEFORMATION

The test simulation was repeated with the chassis frame and floor, Figure 5-24, loaded at the hitch (1000N) and constrained at the centre suspension mounts. The maximum displacement was 12mm at the hitch indicating the addition of the floor significantly increases the overall stiffness of the structure.

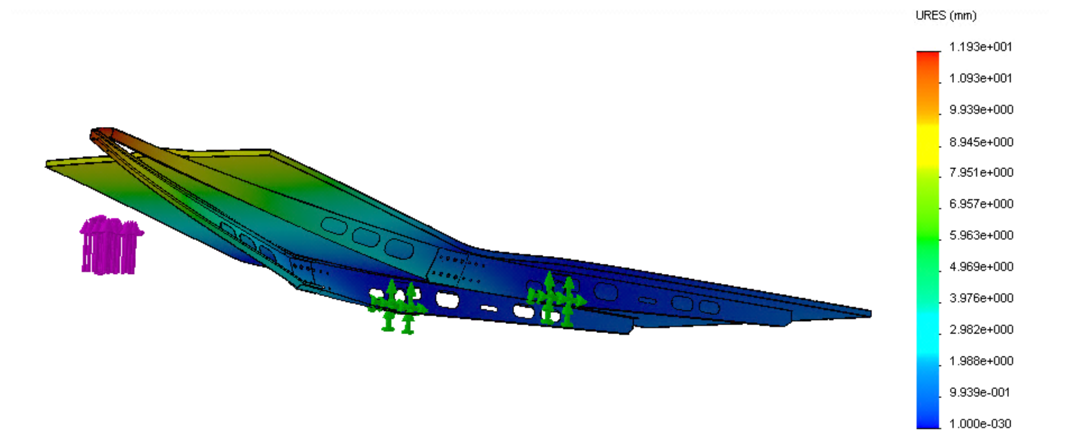


FIGURE 5-24: CHASSIS AND FLOOR DEFORMATION

The simulation was repeated with loads of 500, 1,500, 2,000 and 2,500N as shown in Figure 5-25.

5.8.1.4 COMPARISON WITH STATIC TESTING

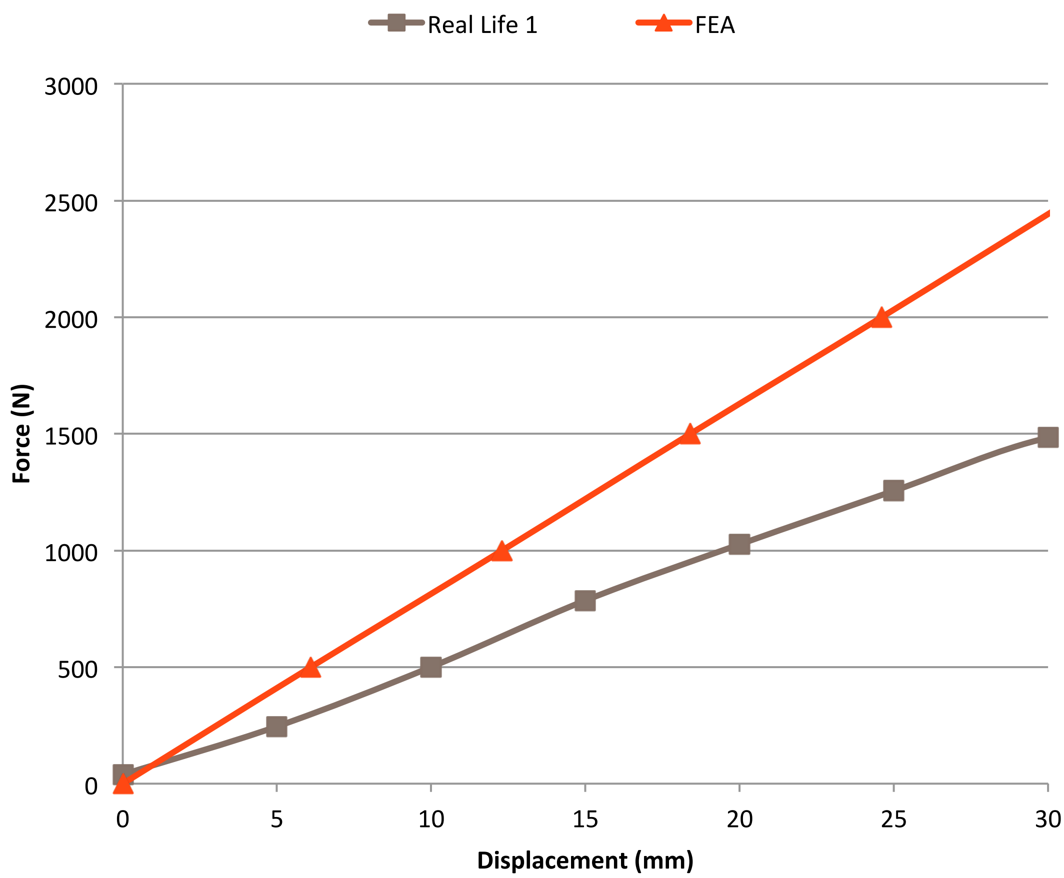


FIGURE 5-25: HITCH LOADING, SIMULATION VS. REAL LIFE

Previous static testing as outlined in chapter 2 demonstrated that, when loaded at the hitch, the chassis deflects in line with the curve shown in Figure 5-25. At a load of 1,000N the chassis and floor structure is shown to have deflected by approximately 20mm. This differs from the value produced by the simulation (12mm) for the following reasons.

- The ply floor is made of a number of panels whereas the simulation model is one complete sheet that will improve load transfer through the structure and increase the overall stiffness. The panels were removed in the model to reduce model complexity.

- The model has been simplified in other areas to reduce solving time and reduce the chance of errors.

Despite the discrepancy between the model and real life static testing, the order of magnitude is the same and the model can be assumed to be a reliable indication of the general performance of the chassis and floor structure. The following section repeats these loading conditions on a model of the proposed prototype chassis and floor.

5.8.2 Sandwich Panel Chassis and Floor Model (Prototype 1)

This first prototype consisted of the sandwich panel arrangement as recommended in 5.5.2. The majority of the structure's stiffness was designed to be derived from the central 'spine' that runs the length of the caravan body.

5.8.2.1 Model Simplification

The model was simplified to improve solving stability by removing any complex design features, Figure 5-26.

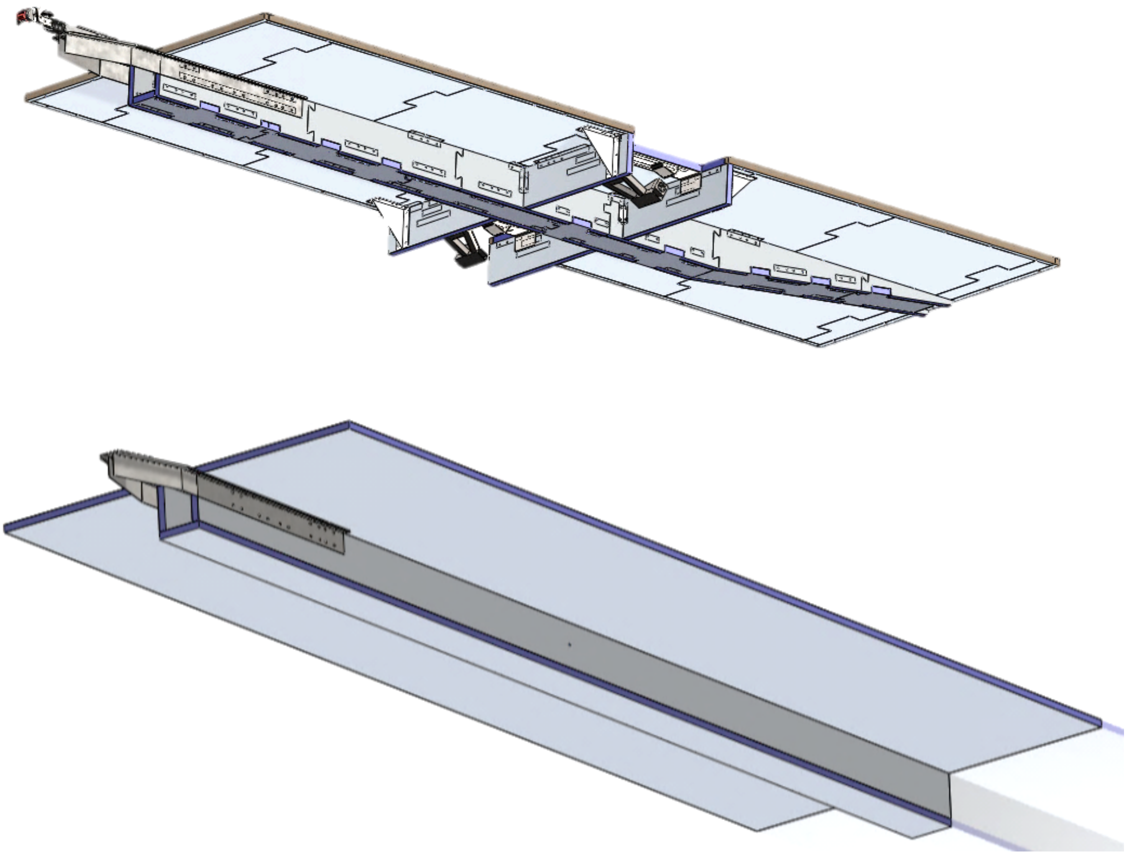


Figure 5-26: Model simplification

5.8.2.2 Loading Conditions

The same loading conditions as outlined in 3.2 were applied to this model as shown in Figure 5-27.

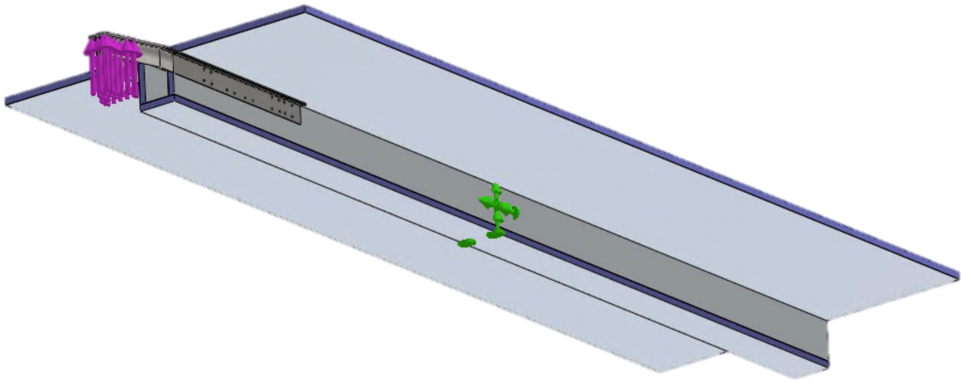


Figure 5-27: Loading conditions

5.8.2.3 Results

The structure was loaded at the hitch with 1,000N and constrained at the centre of the spine. The maximum displacement was shown to be 1mm at the hitch, Figure 5-28 .

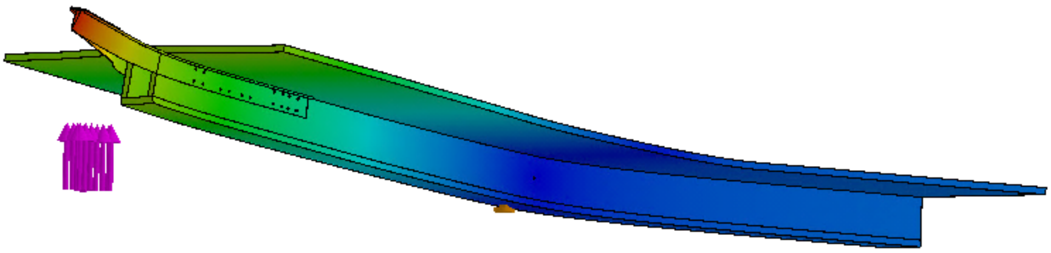


Figure 5-28: Prototype deformation

The simulation was repeated with loads of 500, 1500, 2000, and 2500N. Figure 5-29 below compares the stiffness of the prototype model with that of the original chassis model. The results indicate that the new prototype is predicted to be significantly stiffer than the original chassis when loaded in this orientation. In reality, it is unlikely that the prototype will be stiffer by the magnitude suggested due to model simplification but it indicates that the design intention is valid.

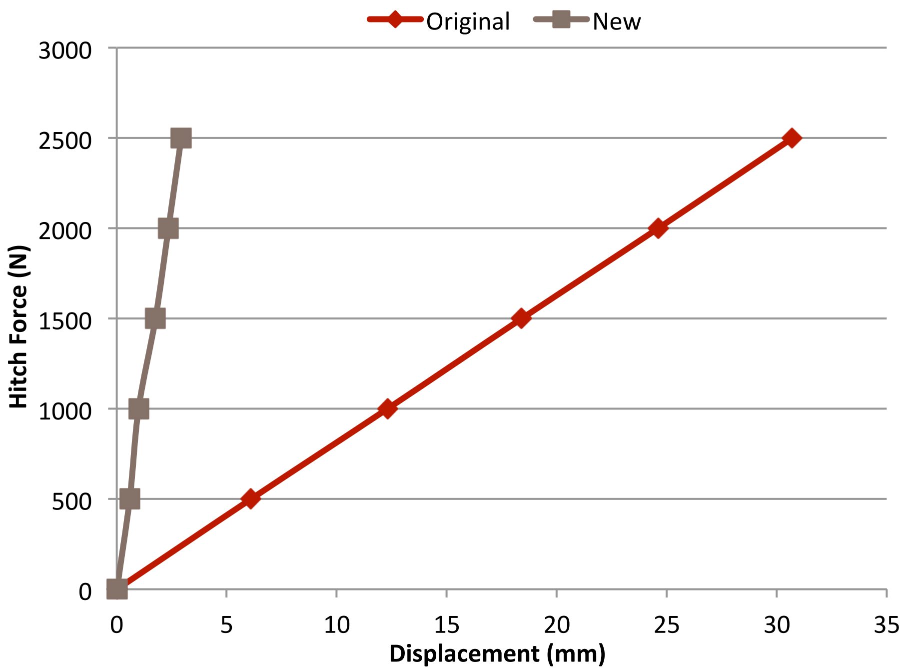


Figure 5-29: FEA model stiffness comparison

5.8.3 Conclusion

It is likely that the deflection shown in Figure 5-29 will be larger when the prototype chassis is tested. Nevertheless the modelling approach has shown to be reliable and it is reasonable to conclude that the new prototype will have improved stiffness characteristics when compared to the original chassis and floor design.

5.9 Conclusion

The results from the FE analysis have indicated that the design intention is justified and that it was reasonable to progress to develop a working prototype. Estimates predict that the proposed design should be approximately 15kg lighter than the equivalent Alko chassis. Once built, the prototype would undergo the same testing as outlined in chapter 2 to ensure that the FE analysis can be validated.

6 : Caravan Prototype (1) Chassis and Suspension Development

6.1 Introduction

This chapter summarises the development of the first full-scale prototype that includes both the chassis and suspension systems. The design choices have been made based on the analysis conducted in previous chapters. Certain aspects of the design had to be modified to accommodate the manufacturing capabilities and materials that were available. It is worth reiterating that the main aims of the development process were to reduce net weight, improve suspension performance and enhance the weather proofing characteristics whilst also retaining features of the current design such as the corner steadies, hitch coupler and ride height.

6.2 Component Systems

6.2.1 Chassis

The chassis system comprised of two main constituent parts; the floor and the spine. It was an intention to make the floor integral to the structure acting as a stiffening component in its own right rather than relying on strength being derived from the 'floor on frame' approach of the current Alko design. The spine structure increases stiffness in areas where the floor is subjected to the highest bending loads, namely along the centre and adjacent to the wheels as discussed in 5.2.4.

Both the floor and the spine were constructed from the same sandwich panel configuration. The panels comprised of high-density expanded polystyrene foam sandwiched between two sheets of 0.8mm thick aluminium, Figure 6-1.

Figure 6-1: Aluminium and Foam Panel

The choice of material was based on the results conducted in section 5.5. This panel configuration was considered to have the optimum stiffness to weight ratio and was also made from commonly used materials. The panels were manufactured at Bailey using the current methods for producing caravan side panels and ceilings. This was a deliberate consideration towards minimising the possible future impact on manufacturing of the system.

The chassis was designed around the Bailey Unicorn Valencia caravan; the caravan used in the initial testing phase of the project.

The floor and spine were combined using a tongue and groove system secured in place with mechanical fastenings, Figure 6-3. The tongue and groove system ensured error free assembly but was also a method aimed to transfer tow-vehicle force into the whole structure more efficiently as shown in Figure 6-2.

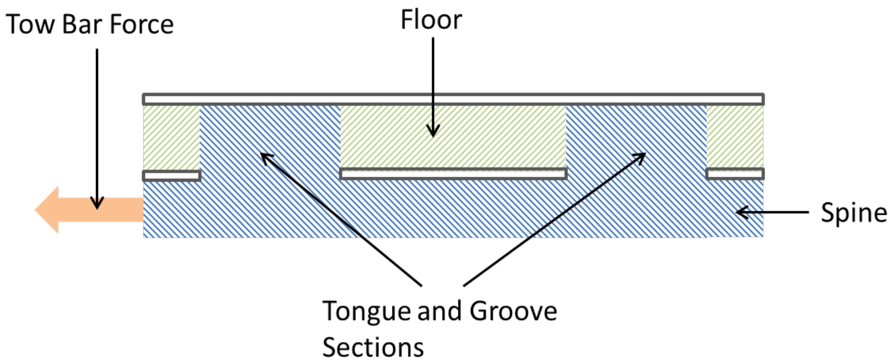


FIGURE 6-2: CHASSIS STRUCTURE CONSTRUCTION

The tow hitch was connected to the chassis through a fabricated steel A-Frame that was bolted to the spine and floor sections, Figure 6-3.

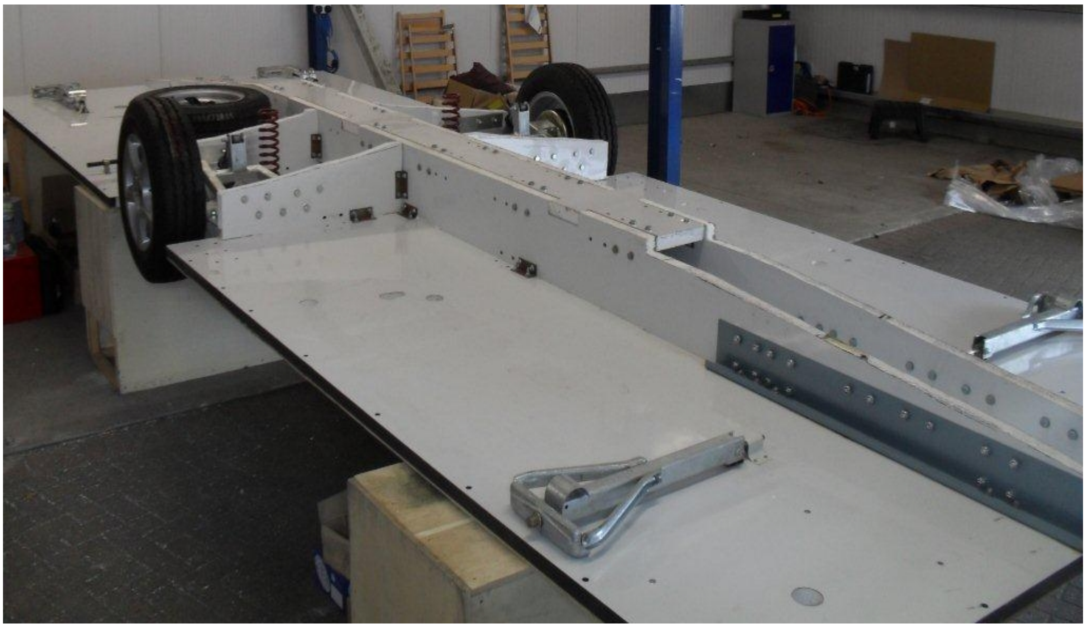


FIGURE 6-3: PROTOTYPE 1

6.2.2 Suspension

The Sprite caravan testing as outlined in chapter 4 influenced the choice of suspension configuration. It was concluded that a trailing arm, damped coil spring arrangement was one that could be optimised very easily and has been a tried and tested method of vibration isolation in a number of industries. The choice of the trailing arm and 'coil-over' arrangement was selected because it is the system which is best suited for confined areas under a vehicle. The suspension was designed with the aim of achieving the following:

- Natural ride frequency of around 1.5Hz
- Maximum bump travel of 60mm
- Maximum rebound of 25mm
- Compatible with the current Alko wheel hub and brake system

The swing arm was bolted on to a fabricated steel sub-frame bracket that was in turn bolted to the floor and spine sections. The bracket also acted as a stiffening structure in the area where road force would be transmitted to the chassis, Figure 6-4.

The first prototype was un-braked as testing would be conducted on site and not on public roads.

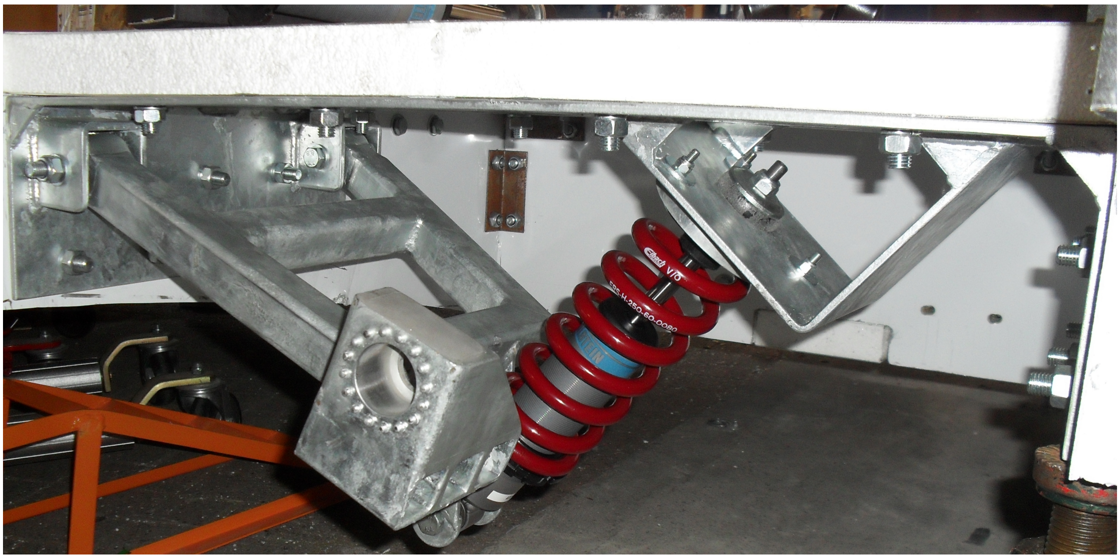


Figure 6-4: Trailing Arm Damped Coil Spring Suspension

6.2.3 Spare Wheel Carrier

The spare wheel carrier was investigated in a separate design project conducted by E Martinez [24]. The project investigated the design attributes of the current Alko system and concluded that there was room for substantial improvement. The new design comprises of a hoist system placed on the underside of the floor. The spare wheel is clamped in place against a locating plate. The same tool that is used to lower the corner steadies operates the system. The user simply winds the wheel down and unclips it from the retainer. The system is approximately 6kg lighter than the Alko product and far more user friendly.

Figure 6-5: Spare Wheel Carrier

6.2.4 Next Steps

Chapter 7 outlines the testing that was conducted on the prototype and compares the results with the benchmark data of the Alko system as discussed in chapters 2 and 3.

7 : Prototype (1) Performance Testing

7.1 Introduction

This chapter investigates the performance characteristics of the first prototype chassis (prototype 1) and compares the results to the original Alko chassis system. The study includes results from both the static chassis loading and the dynamic testing of the suspension system. The test procedures are identical to those conducted in the investigative phase of the project as outlined in chapter 2.

7.2 Chassis Stiffness Testing

The FE analysis conducted in chapter 5 indicated that the new prototype design would be stiffer than the Alko system under the same loading conditions as highlighted in Figure 7-1. An aim of this investigation was to verify these results through experimental testing to justify the design intent. In order to quantify the relative stiffness of the new chassis, the prototype was subjected to the same loading regime as outlined in chapter 2. The results were compared to the benchmark data set from the Alko system.

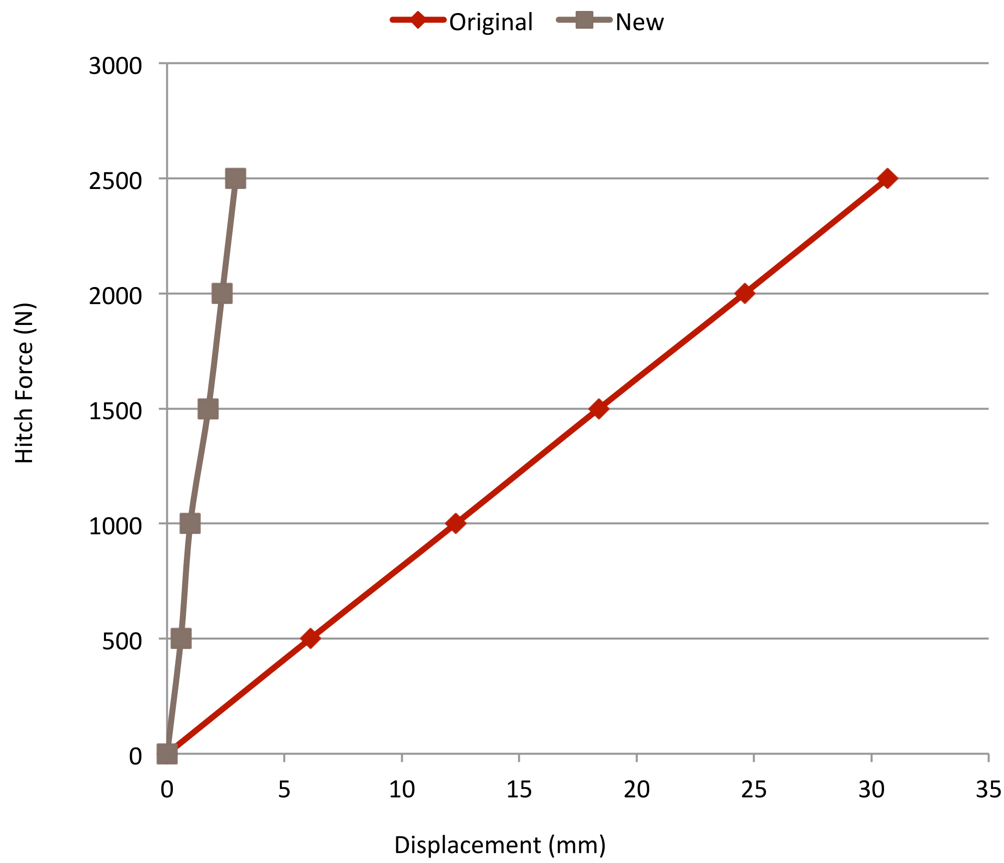


Figure 7-1: Comparison of FEA Models: Stiffness Characteristics

7.2.1 Experimental Procedure

The chassis was raised on all four corner steadies with the wheels removed and the suspension brackets anchored to the floor as shown in Figure 7-2 below. The hitch was loaded using a vertical jack placed on a balance. The load was gradually increased and recorded at 5mm intervals. The test was repeated with the load applied at the front and rear corners. The intention was to bend the chassis and floor structure rather than lift it off the ground thus exposing the stiffness properties of the system. This allowed the relative stiffness to be calculated and compared with the benchmark data for the Alko chassis.

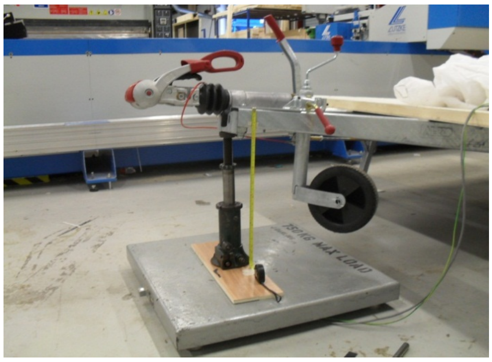


Figure 7-2: Chassis Loading Setup

7.2.2 Results

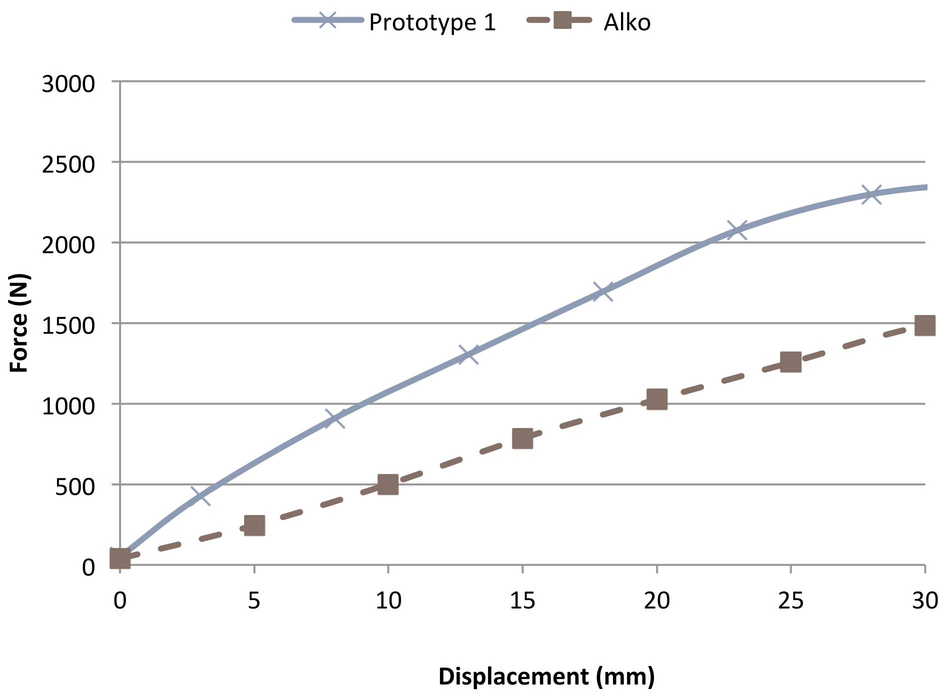


Figure 7-3: Hitch Loading

Figure 7-3 above indicates that, when loaded at the hitch, the prototype exhibits a stiffness that is approximately twice that of the Alko system.

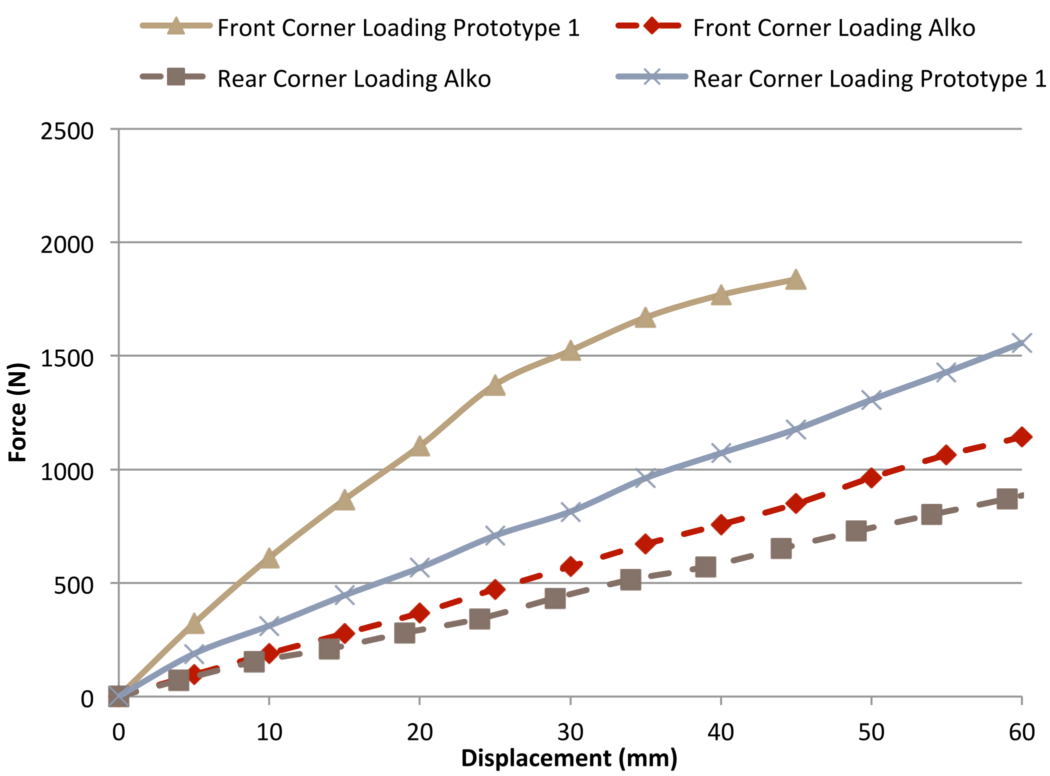


Figure 7-4: Corner Loading

Figure 7-4 above indicates that under the two different corner-loading conditions (front and rear) the prototype chassis is again approximately twice as stiff as the Alko arrangement.

7.3 Dynamic Testing

The dynamic testing process was a continuation of the approach used in the investigative phase of the project as outlined in Chapter 3. During this process it was concluded that the most severe and therefore worst-case condition was the pothole trial that yielded the largest hub displacement and greatest bump force on the suspension system. The metrics used to indicate performance were the suspension travel, damping rate and interior body acceleration.

The test process used the same method as before but also measured vertical acceleration using an on-board accelerometer. This gave a direct measure of the vibration isolation characteristics of the suspension system.

The testing was conducted on both the Alko system and the new damped coil spring system on identical caravans of the same (fully laden) weight (1560kg).

7.3.1 Experimental Setup

A linear displacement transducer was connected to the wheel hub and connected to an on-board data logger, Figure 7-5, which sampled the output at 100Hz. The data logger also had the capability to measure vertical acceleration up to a maximum value of 2g.

Figure 7-5: Data Logger

The car and caravan combination was accelerated up to 15mph and passed through the pothole as shown in Figure 7-6. This pothole is identical to that used at Millbrook proving ground however the surrounding road surface was of poorer quality.

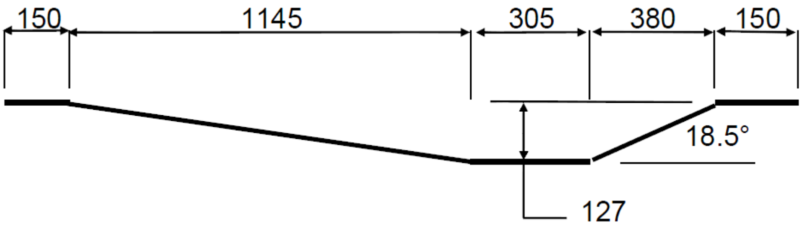


Figure 7-6: Pothole Dimensions

It was found that at higher speeds the 2g limit on the accelerometer on the data logger was not sufficient. An accelerometer with a 5g limit was acquired and the trials were repeated.

7.3.2 Results

7.3.2.1 Hub Displacement

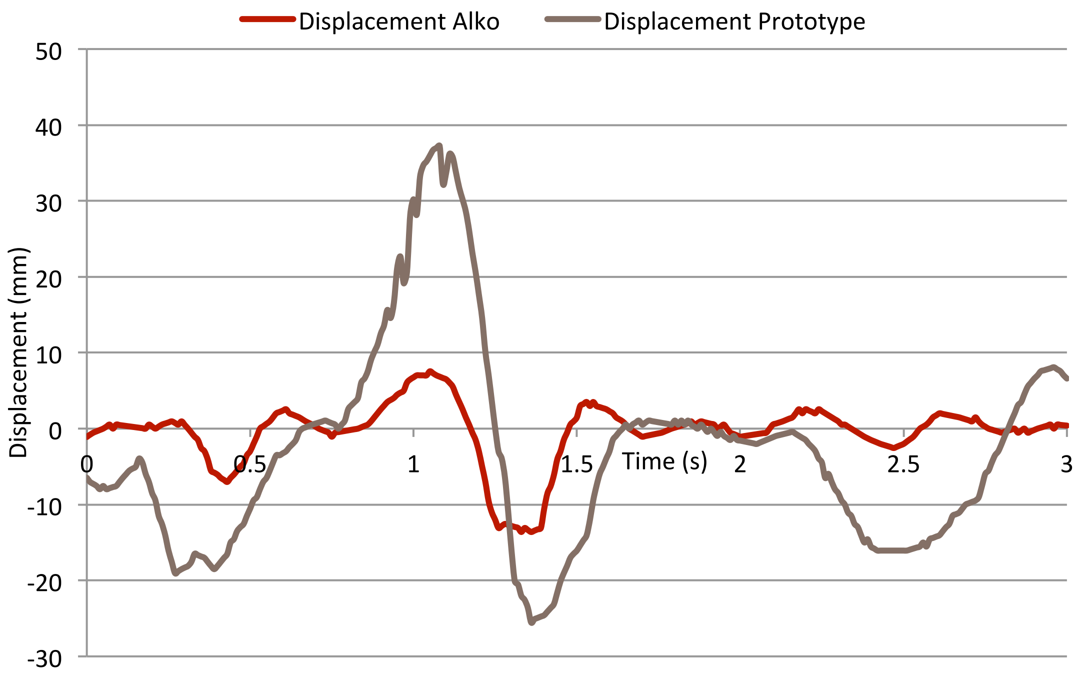


Figure 7-7: Hub Displacement through Pothole at 5mph

Figure 7-7 above indicates that at 5 mph the prototype suspension system exhibits bump travel of approximately 37mm and rebound travel of 24mm. The Alko system achieves bump travel of 8mm and rebound travel of 12mm.

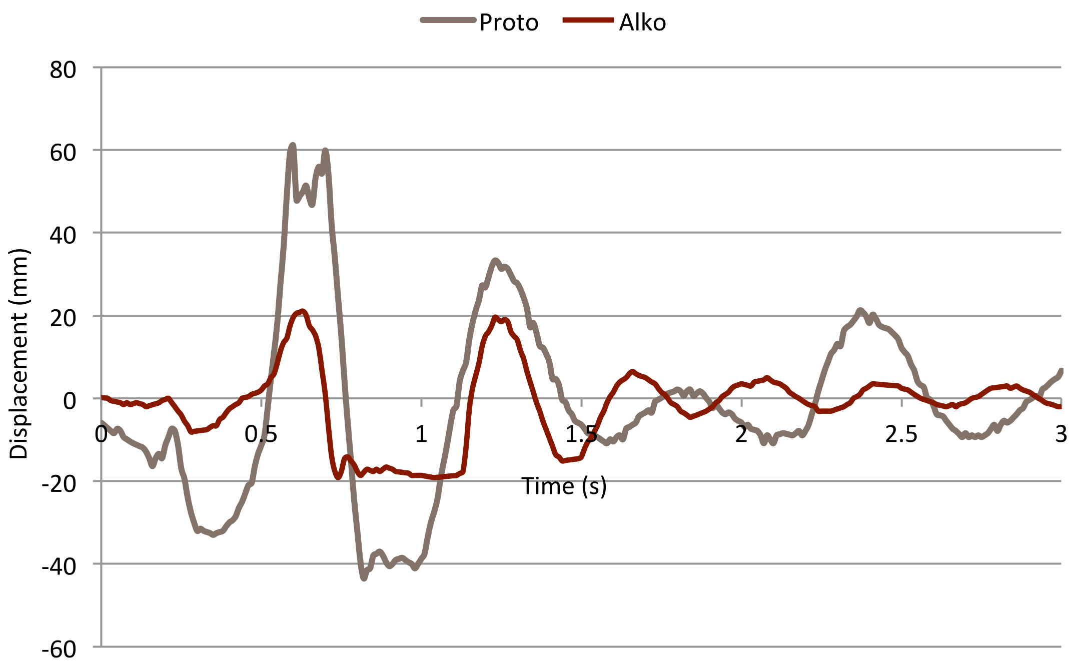


Figure 7-8: Hub Displacement through Pothole at 15mph

Similar results to those seen at 5mph were exhibited at 15 mph as shown in Figure 7-8. The prototype system achieved bump and rebound travel of 60 and 40mm respectively whereas the Alko system varied between 20mm in bump and 20mm in rebound. The oscillations at the maximum amplitude of the prototype response are likely to be due to the engagement of the bump stops at maximum positive (bump) and maximum negative (rebound) travel. The Alko system is not fitted with bump stops and is unlikely to reach full bump even under the harshest of road conditions.

The response of the system following the impact was analysed in order to calculate the ride natural frequency and damping ratio. The system was designed to achieve a natural frequency of 1.5Hz and a damping ratio of around 0.25; values that are typical of a car with good ride characteristics [17]. From Figure 7-8 the ride natural frequency was calculated to be 1.6Hz and the damping ratio was 0.12. This indicated that the spring stiffness and wheel rate is suitable for the caravan but the system may require a higher rate of damping.

It was observed that, following the tests, the floor of the caravan fitted with the Alko system had a large crack running between the chassis bolts where the main steel members are bolted to the structure, Figure 7-9. There was also failure in the floor in the area adjacent to the wheel box. The force transmitted through the chassis member when travelling over the pothole was large enough to propagate a crack in the floor sandwich panel. Although this caravan was not fitted with furniture, which stiffens the structure, this is a possible area of concern for the current design, as the flooring material on production models will mask any cracks in the structure.

Figure 7-9: Failure of the Plywood Floor in the Alko System

7.3.3 Acceleration

The caravan was towed over a speed bump (not pothole) at 15mph and the acceleration of the caravan interior was measured using a 5g-limit accelerometer connected to the on-board data logger. The accelerometer was placed directly over the wheel and securely fixed to the interior wall. Figure 7-10 shows the normalised results from both the Alko system and the prototype chassis.

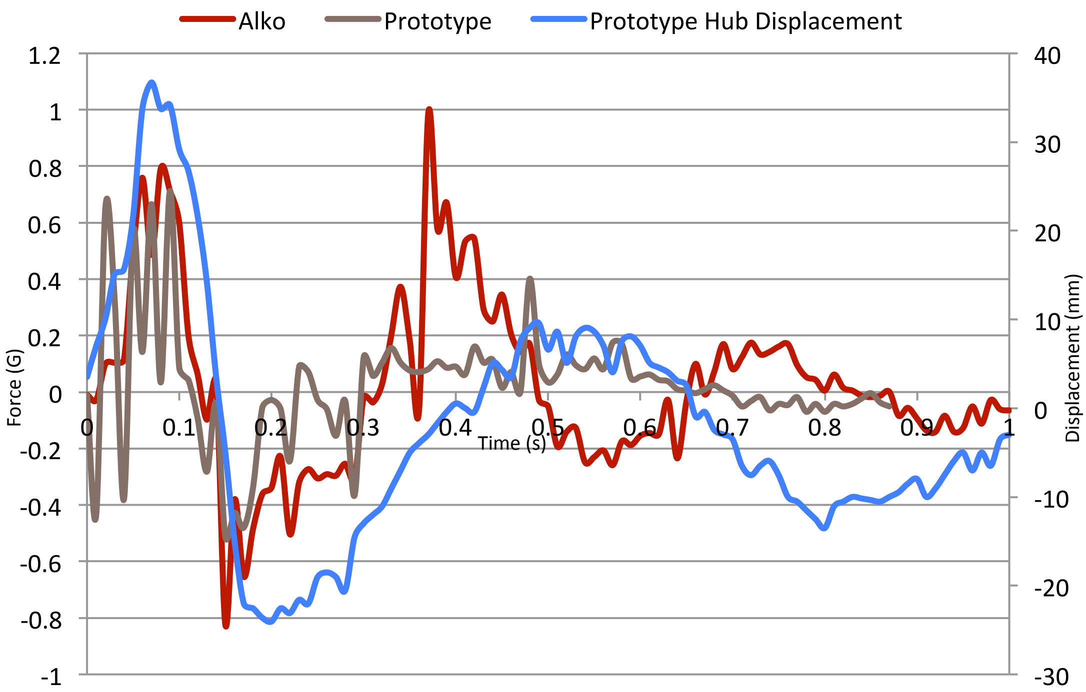


Figure 7-10: Acceleration in Caravan Interior

Figure 7-10 above shows the vertical acceleration of the caravan body (above the wheel) on both the Alko system and the prototype as it passes over the speed bump. The prototype hub displacement is shown on a secondary axis to indicate where the acceleration peaks occur relative to the wheel motion. The Alko hub exhibits a similar displacement profile but with greatly reduced travel. The results indicate that the maximum acceleration experienced by the prototype system was around 0.7g compared with 1g on the Alko system. Although this difference is not dramatic, the transient response of the prototype system after impact is better than that of the Alko system. This in turn implies that the magnitude of the forces transmitted into the caravan body is less in the prototype system.

Both the Alko system and the prototype exhibit a secondary response of approximately 30Hz. It was suspected that this could be attributed to the wheel hop frequency but the oscillations were present when the caravan was stationary indicating that there was a level of background noise within the system.

7.4 Conclusion and Next Steps

The results from the static testing indicated that the prototype chassis (1) exhibited a higher stiffness than the Alko system when loaded in the three different conditions. This indicates that the design intent of the prototype is justified and that further weight could potentially be removed from the system through reducing its bulk and therefore reducing its stiffness properties. The results also indicate that the FEA method is valid and can be used to develop future iterations of the design.

The results from the dynamic testing indicated that the optimised damped coil spring suspension system exhibits enhanced dynamic performance when compared with the traditional Alko system. This has been generated from a reduced spring stiffness, increased travel and more sophisticated damping. Although further testing on different road conditions is required it is recommended that a coil spring system be used on the next prototype iteration. The configuration of the spring and damper should be reviewed in order to reduce stress concentrations on the control arm and improve ease of manufacture. It was concluded that an alternative accelerometer should be sourced to ensure accurate and reliable data.

An area that was not sufficiently investigated was fatigue and the effects of general road use on the structure. It is recommended that the development of the next prototype include high mileage tests to investigate any potential areas of weakness in both the chassis structure and the suspension system. Following this, it is recommended that the system undergo accelerated life tests to investigate its viability as a competitive alternative to the Alko system.

8 : Prototype 2 Development

8.1 Introduction

This chapter summarises the development and testing of the second prototype (prototype 2). Prototype 2 utilises the same key design principles as prototype 1 namely the use of the integrated floor and spine structure and trailing arm, damped coil spring suspension. There was however several areas that were adapted from the original design to further reduce weight improve suspension performance and improve ease of manufacture. The second prototype also included a brake system in order to make the caravan road legal. This chapter outlines the key design changes and investigates the second stage of prototype testing.

8.2 Design Issues with Prototype 1

8.2.1 Weight

Although the first prototype was approximately 10kg lighter than the Alko system it was concluded that this could be reduced even further through several key design changes. The fact that prototype 1 was almost twice as stiff as the Alko system implied that there was room to reduce the weight of the system and not compromise greatly on structural stiffness. The target was to reduce the weight by a further 40kg and also add a brake system.

The main area for weight reduction was the mechanical fastenings and bracketry that featured heavily on prototype 1 as shown in Figure 8-1. There were approximately 70 brackets each with 4 bolts that greatly increased the weight of the chassis. The bulk of the spine and density of the core material were also areas for improvement and the enclosed box structure of the spine was concluded to be overly cumbersome and would prohibit access to the brake system and a number of service channels.

The bracketry and other metal fabrications were also considered to be too bulky and over engineered for their requirements.

FIGURE 8-1: PROTOTYPE 1 SHOWING BOLTS AND BRACKETS

8.2.2 SUSPENSION CONFIGURATION

The required spring rate and suspension travel meant that the optimum coil spring was very large and required a substantial preload before it could be fitted on the damper and swing arm, Figure 8-2. Moreover the location of the spring and damper in between the two bushes meant that a substantial turning moment was imparted on the centre of the swing arm. This caused the rubber bushes to twist towards the centre of the caravan that in turn caused the wheel to develop a negative camber, Figure 8-3. The torque imparted on the outer arm of the swing arm also caused two welds to fail on the first prototype as shown in Figure 8-2.

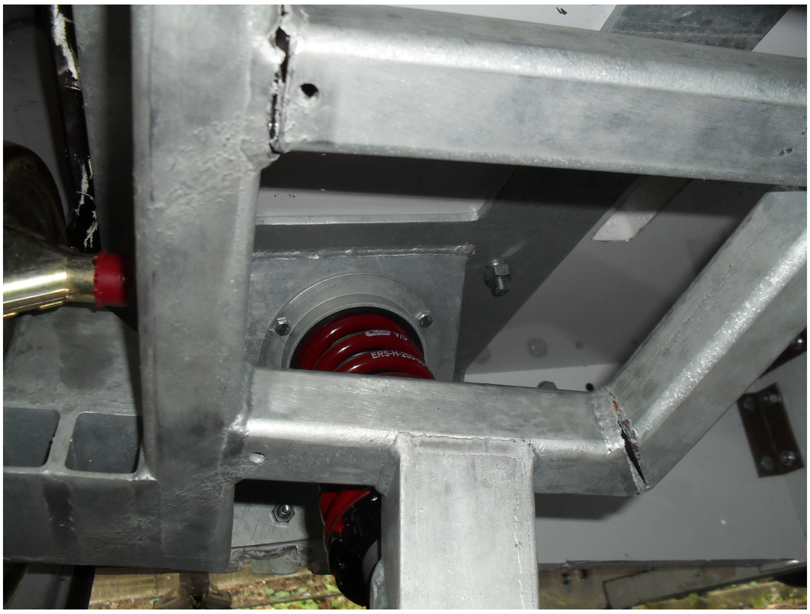


FIGURE 8-2: FAILED WELD ON SWING ARM

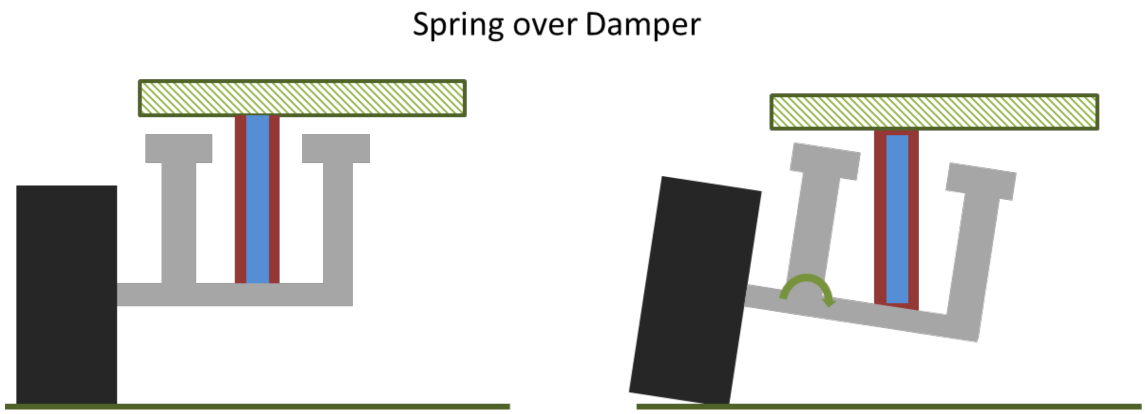


Figure 8-3: Negative Camber Imparted on Wheel

8.3 Prototype II Design

8.3.1 Chassis

The majority of the mechanical fastenings were replaced with a high performance epoxy structural adhesive. This was chosen through testing and with the help of Alpha adhesives. The aim was to bond the spine section to the underside of the floor using aluminium 'top-hat' sections as shown in Figure 8-4. In the recesses of the tongue and groove polyurethane adhesive was used, as this is able to form a good bond between aluminium and polystyrene. Steel bracketry was used in key areas of structural support such as by the intersection of the spine components and the hitch A frame members. This configuration resulted in a weight saving of 45kg compared to the equivalent Alko chassis.

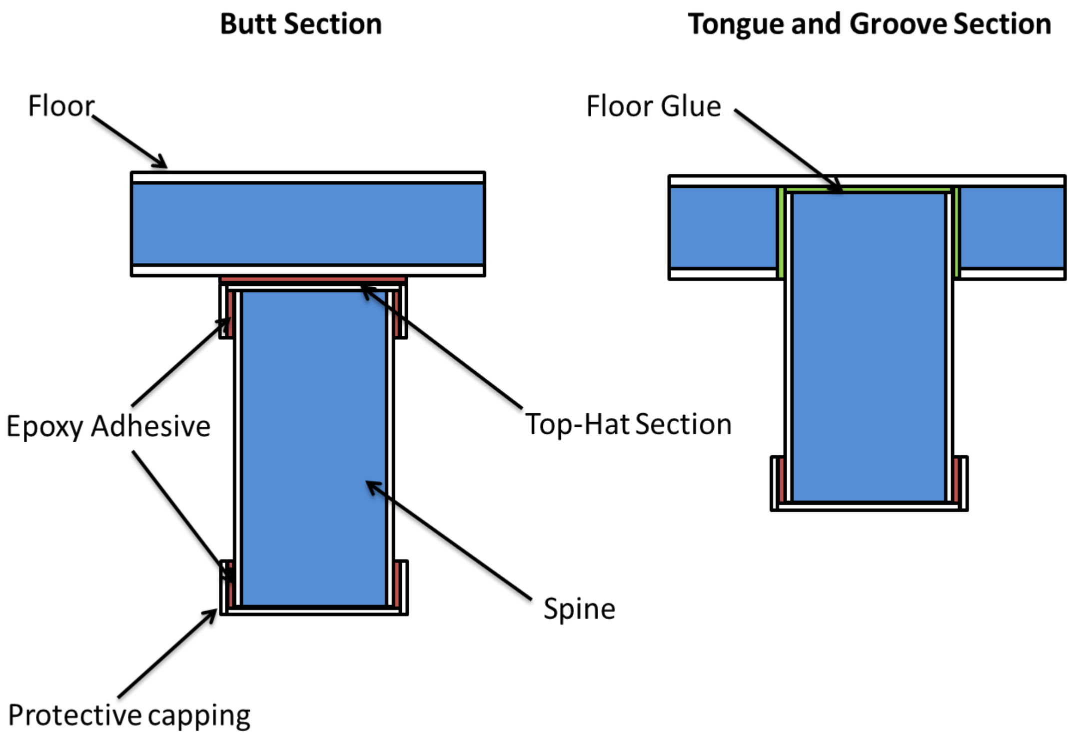


Figure 8-4: Chassis and Floor Joining System

8.3.2 Suspension

The spring and the damper were separated in order to move the spring outbound towards the wheel, Figure 8-5. This reduced the moment imparted on to the swing arm and also made the assembly and installation of the suspension a lot easier. Moreover the access to the system for maintenance and replacement of parts is greatly improved. Brakes were also added.

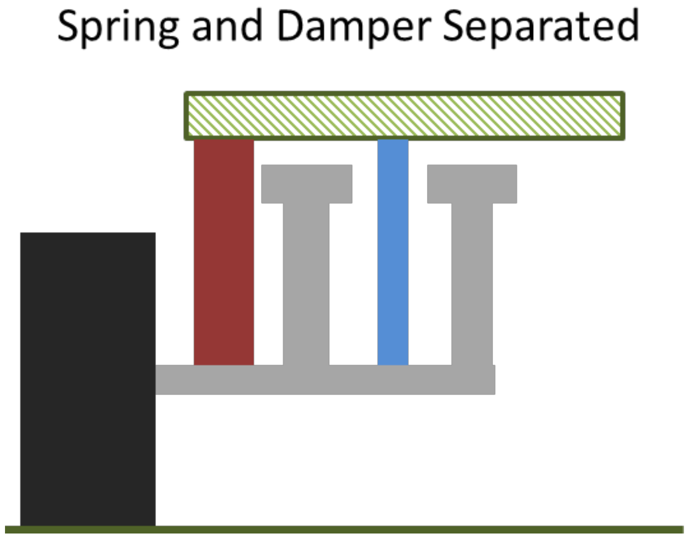


Figure 8-5: New Suspension Configuration

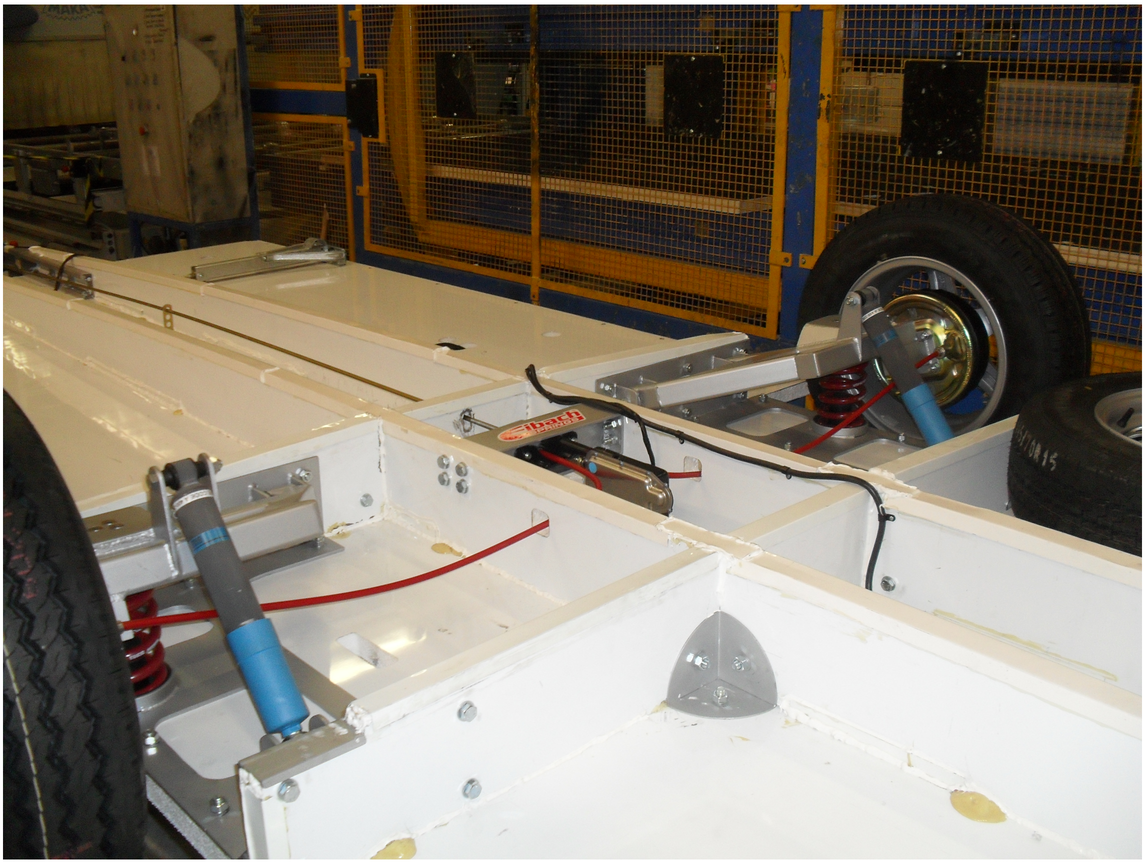


Figure 8-6: Prototype II Showing New Suspension Configuration

8.4 Prototype II Testing

8.4.1 Static Testing

Static testing followed the same procedure as outlined in chapters 2 where the hitch and corners were loaded as the central axle area was secured to the floor.

Figure 8-7 shows the force vs. displacement when loaded at the hitch. Figure 8-8 shows the force vs. displacement when loaded at the corners. Figure 8-9 shows the force vs. displacement when loaded at the hitch with a full caravan shell connected to the chassis.

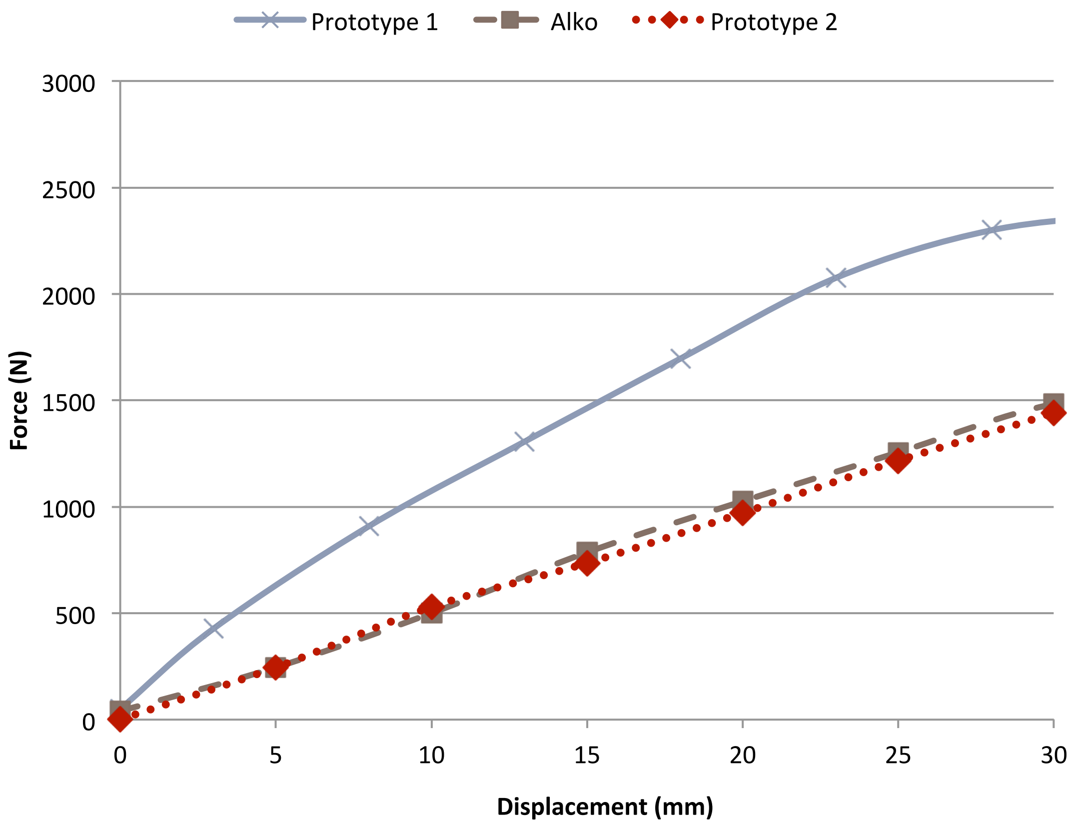


Figure 8-7: Hitch Loading

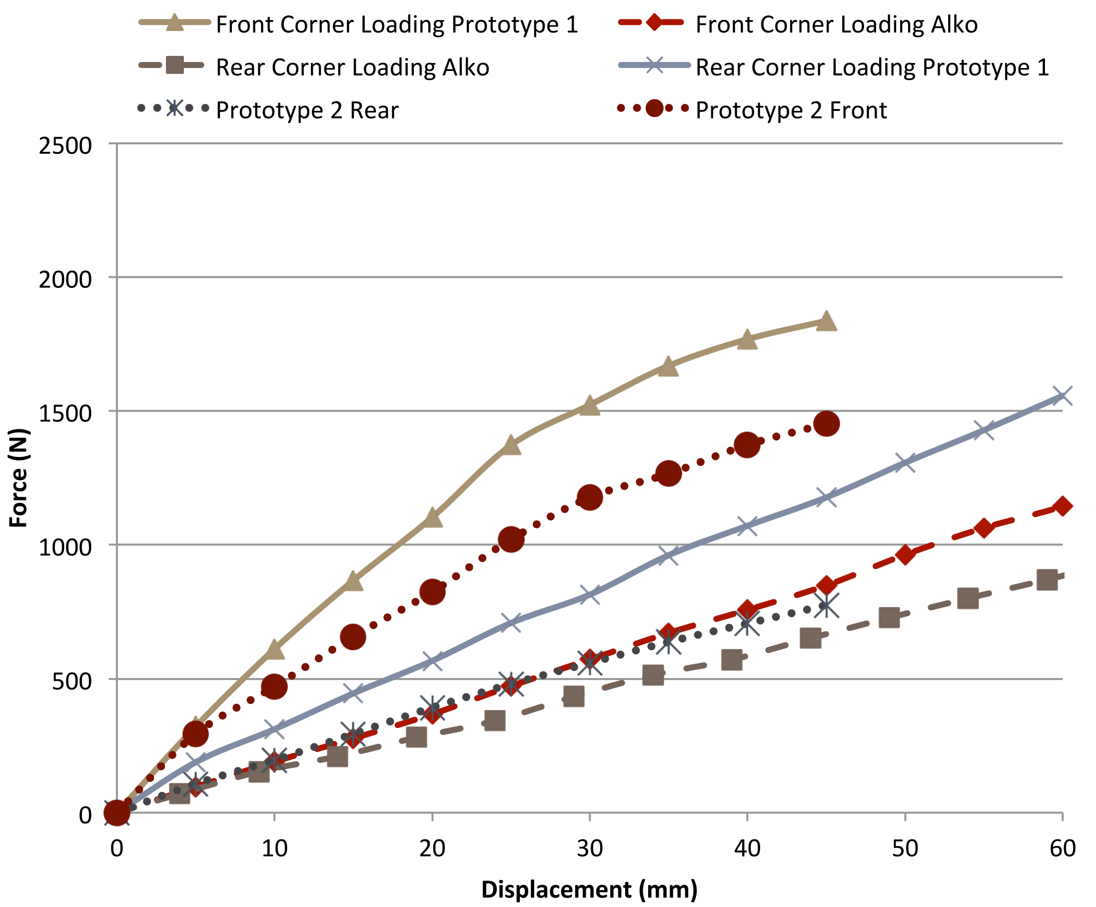


FIGURE 8-8: CORNER LOADING

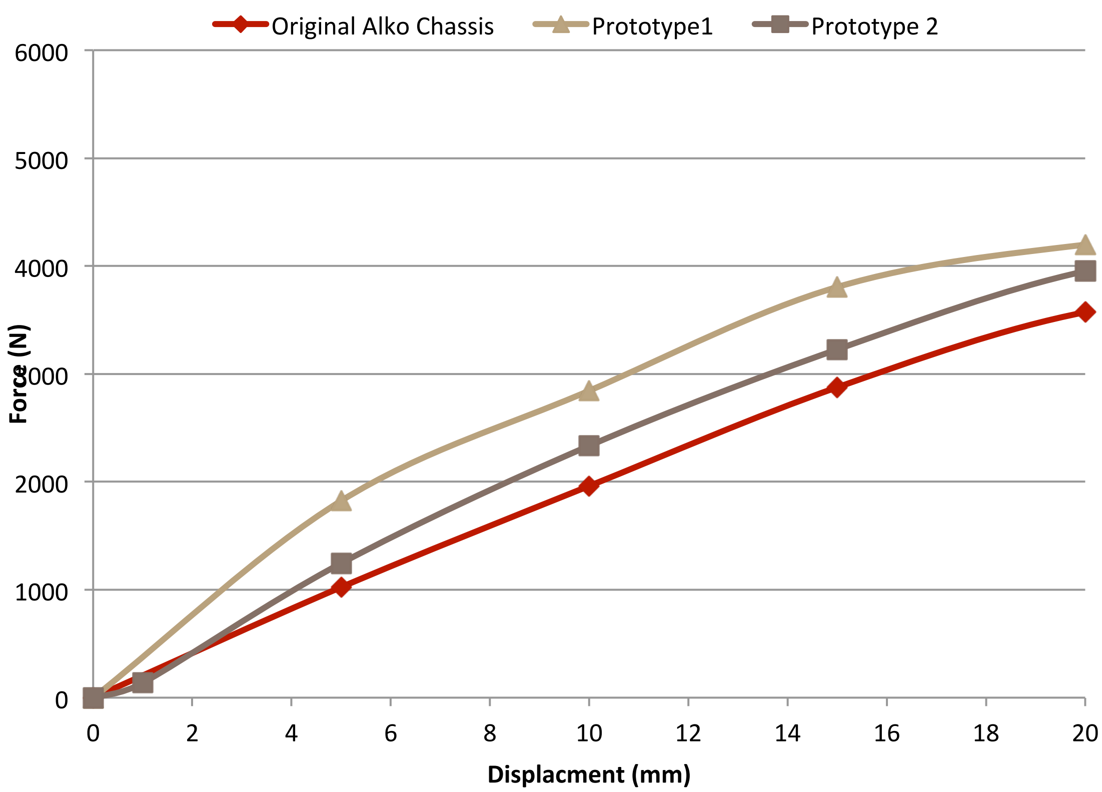


FIGURE 8-9: FULL SHELL LOADING (HITCH)

8.4.2 Dynamic Testing

8.4.2.1 Test Setup and Procedure

The prototype weight was increased to the weight of the standard Bailey Unicorn Valencia (1409kg) with near-side, off -side and nose weights being matched as closely as possible. The prototype was fitted with an accelerometer above the wheel arch as shown in Figure 8-10 and Figure 8-11 below. The accelerometer was linked to data acquisition instrumentation that sampled the acceleration signal at 100Hz. The same telemetry arrangement was installed in a standard Unicorn Valencia caravan fitted with the Alko chassis and suspension system.

Figure 8-10: Prototype Instrumentation

Figure 8-11:Prototype Interior

The caravans were towed around an 18-mile circuit as shown in Figure 8-12 below. The circuit included dual carriageway, single lane A-roads and winding country B roads. Although it was impossible to match speeds at all places along the journey, an attempt was made to stay as close to the respective speed limits as possible (60mph for a dual carriage way with a trailer). It should be noted that the original Valencia model was a production caravan and therefore potholes and other road defects were purposely avoided during the test. A user experience test was also conducted to establish how the prototype 'felt' to tow to an experienced caravan user.

Figure 8-12: Test Route

8.4.2.2 Results

Figure 8-13 shows the acceleration data recorded over the entire duration of each test. As it was impossible to match speeds the data points are not synchronized but the graph does provide a good indication of the vibration isolation characteristics of both the prototype and the original caravan fitted with the Alko system.

Figure 8-13 shows that, on first appearance, it would appear that the Alko system exhibits better vibration isolation characteristics than the prototype system. In order to fully understand the response of each system the data was analysed in the frequency domain as shown in Figure 8-14.

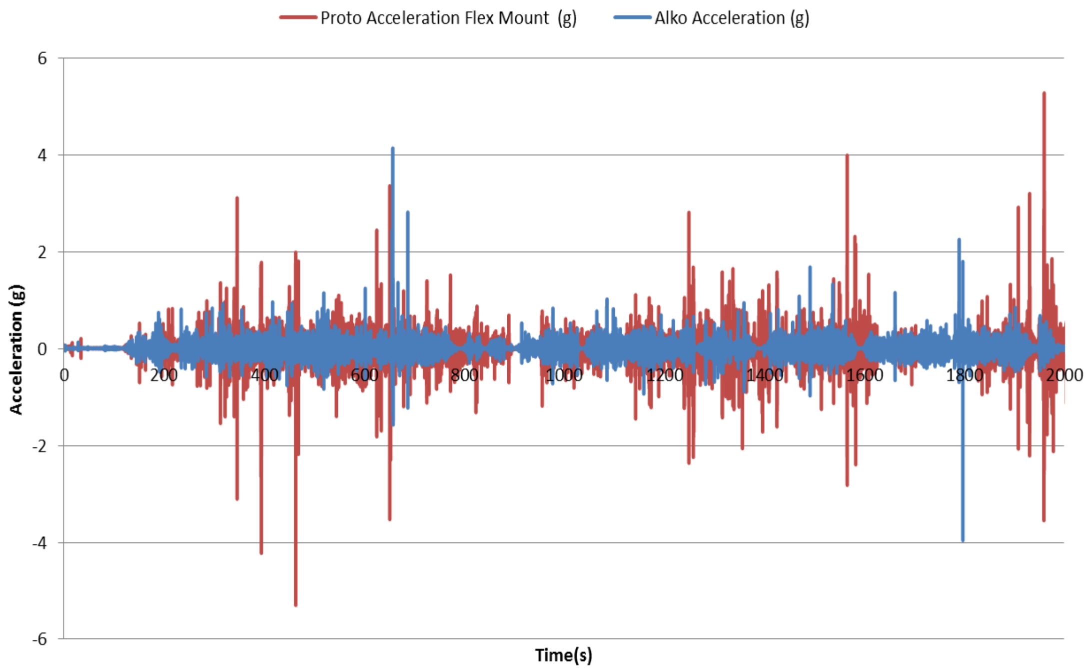


Figure 8-13: Acceleration Data (Time Domain)

Figure 8-14 indicates that the Alko system exhibits a resonance at approximately 3Hz. This is attributed to the body bounce mode and indicates that the suspension system provides minimal isolation from the road defects. Figure 8-14 shows that the body bounce mode exhibited by the Alko system is dramatically reduced in the prototype system, which would suggest that the prototype suspension is better optimised for the road. There is, however, a resonant peak at 15-30Hz, which is not as prominent on the Alko system. It was decided to investigate the accelerometer mounting stiffness as the mounting conditions in each caravan were slightly different, as shown in Figure 8-15 below.

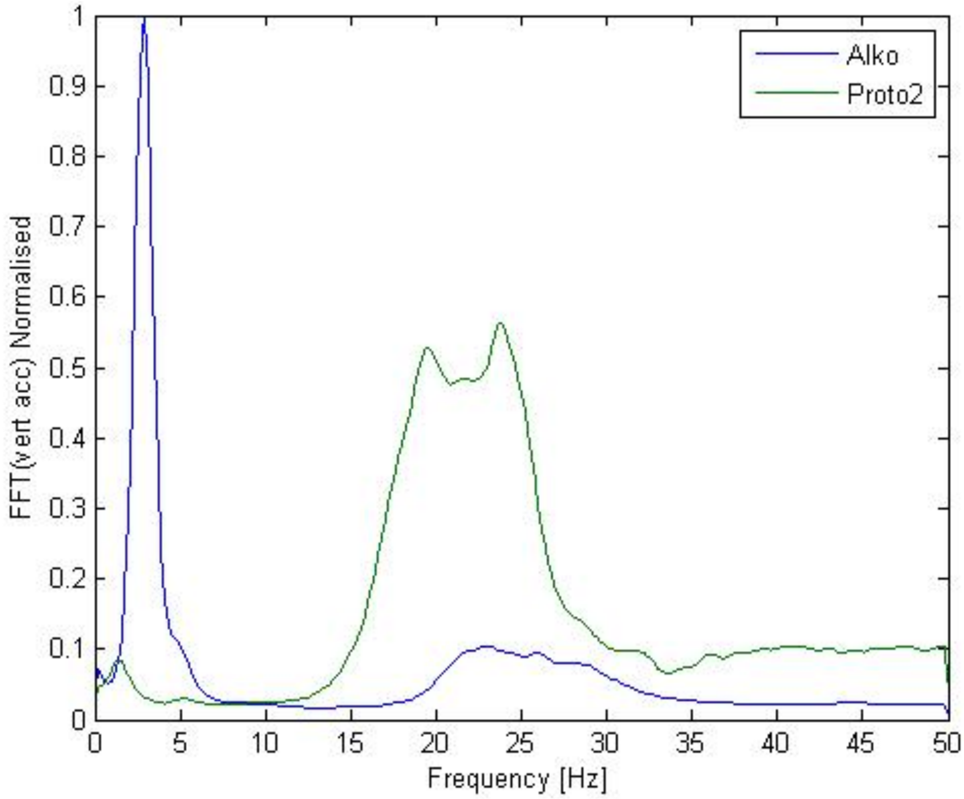


Figure 8-14: Acceleration Data (Frequency Domain) [25]

Figure 8-15: Different Mounting Locations

The response from the accelerometer after exciting the mounting platform is shown in Figure 8-16 below. There is a clear resonance at 22Hz, which would suggest that the peak in Figure 8-14 is attributed to the vibration of the mounting platform.

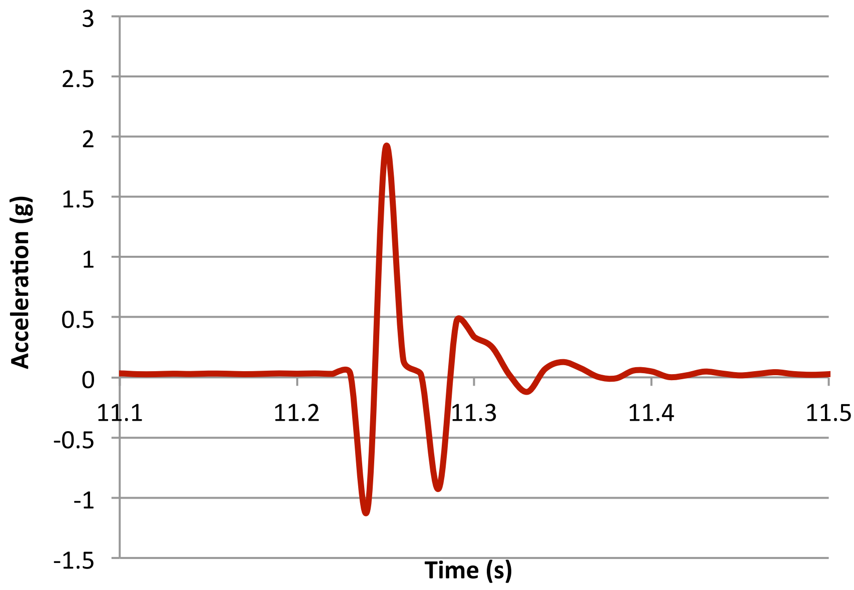


FIGURE 8-16: RESONANCE OF MOUNTING PLATFORM

The mounting platform of the accelerometer was adapted to match the stiffness of the Alko system (Figure 8-17) and the tests were repeated.

FIGURE 8-17: STIFFER PLATFORM

The results of the repeat of the road test are shown in Figure 8-18 below. Figure 8-18 indicates that the average acceleration inside the caravan measured in the prototype system is now less than that measured in the Alko system. This is also confirmed by the data shown in frequency domain in Figure 8-19.

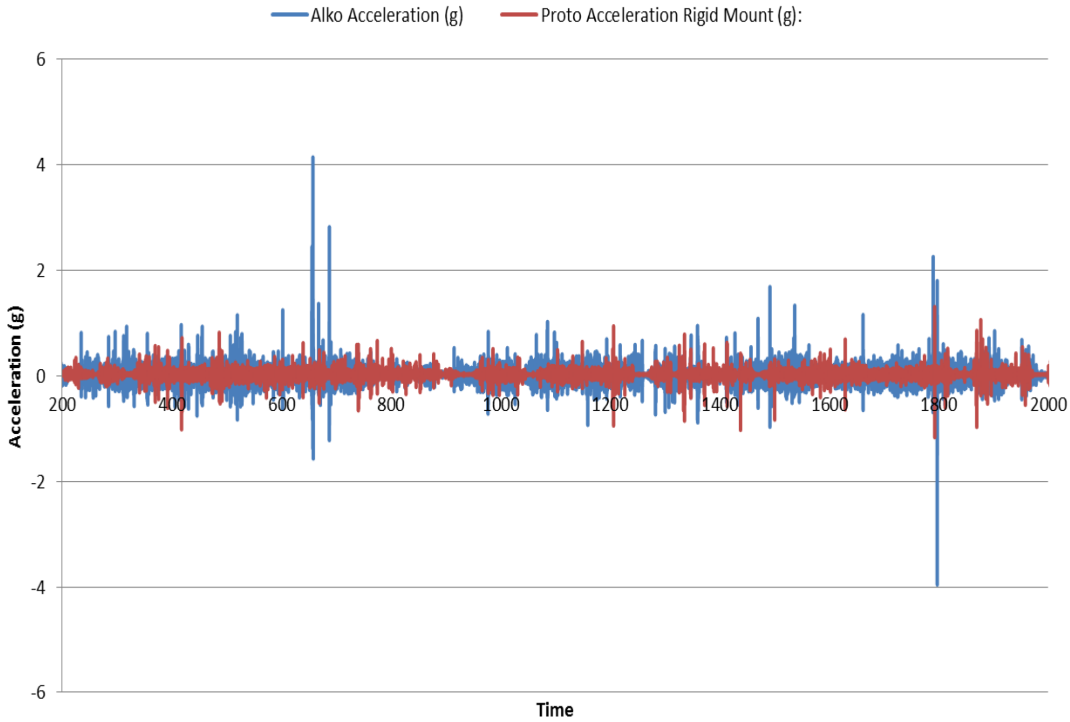


Figure 8-18: Acceleration Data in Time Domain with Stiffer Mount

Figure 8-19 below shows that the resonant peak exhibited in Figure 8-14 can be attributed to the vibration of the mounting platform. The use of the stiffer mounting indicates that the prototype system is significantly better at isolating road vibrations compared to the Alko system. There is a small resonance at around 2Hz but this an order of magnitude lower than equivalent resonance of the Alko system. The results also indicate that the system is well damped although this could be investigated in more detail to optimise the dynamic stability performance.

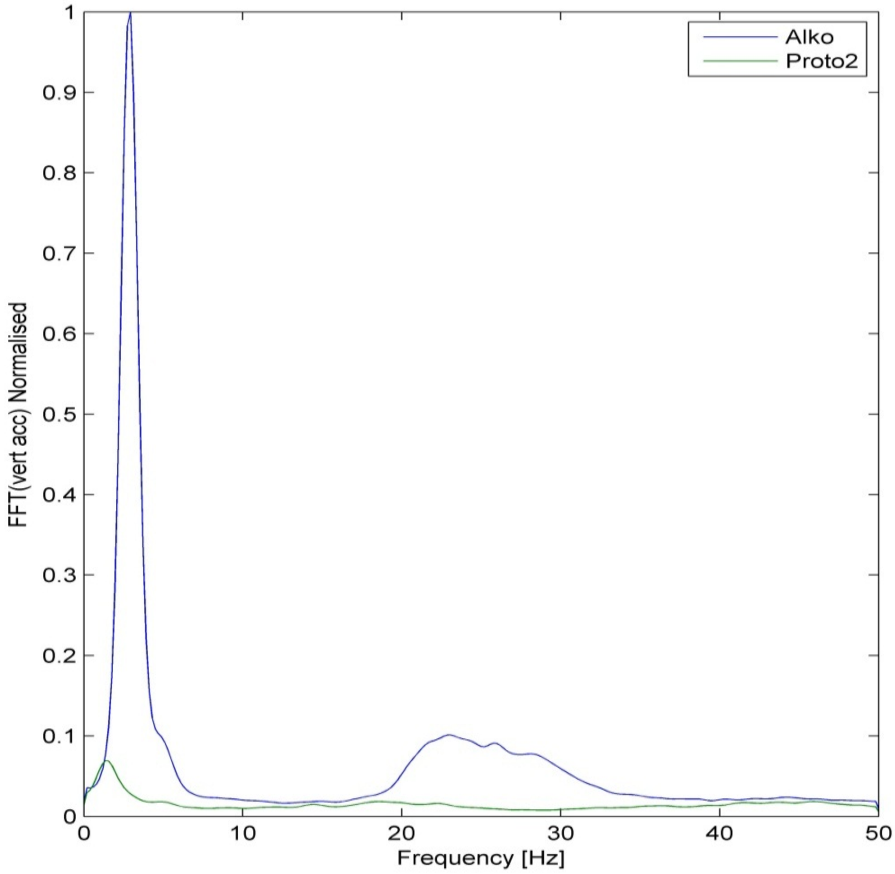


Figure 8-19: Acceleration Data in Frequency Domain with Stiffer Mount [25]

It was concluded that the substantial difference in performance of the two suspension systems meant that there was opportunity to increase the stiffness of the prototype spring to increase the high-speed stability of the caravan and reduce the chance of engaging the bump stops over large road defects. The 120kN/m coil springs were replaced with springs of stiffness 140kN/m. This increased the wheel rate from 72kN/m to 83kN/m. The results shown in Figure 8-20 indicate that the isolation characteristics are very similar to the 120kN/m springs with only a slight increase in harshness at 2Hz. Further investigation needs to be carried out to assess the high-speed dynamic stability.

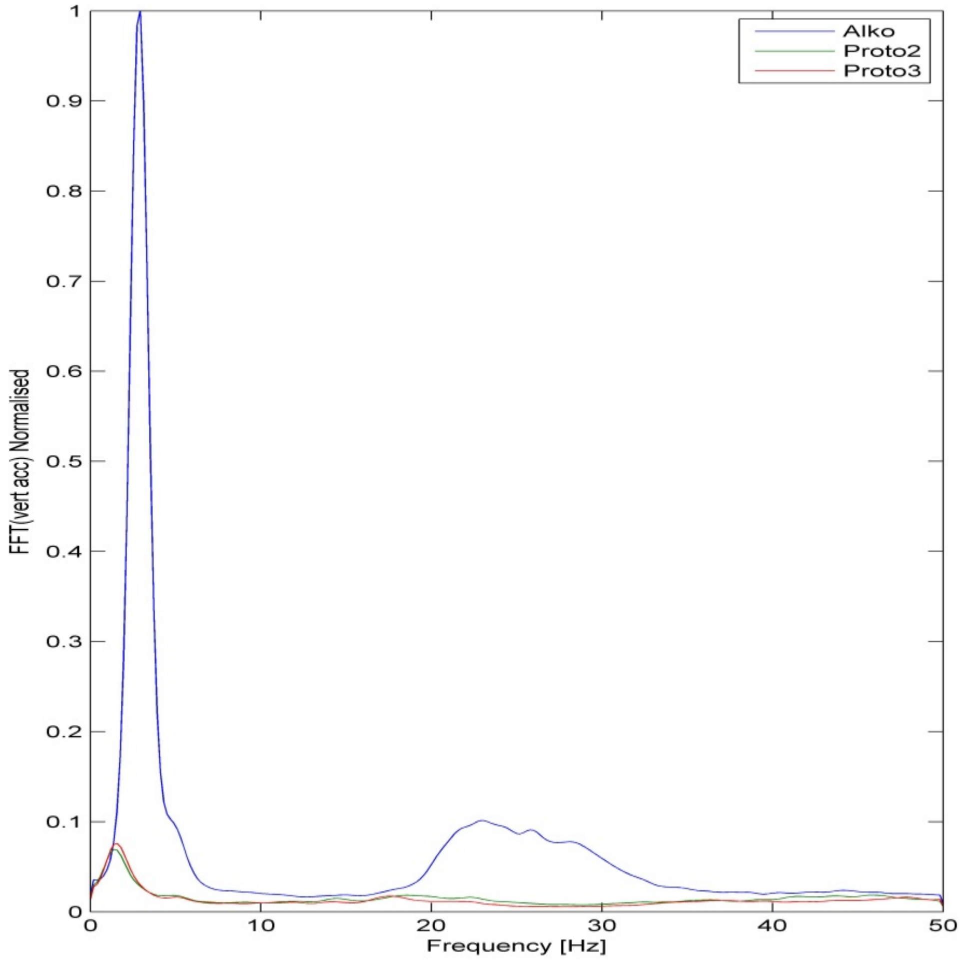


Figure 8-20: Acceleration Data with 140kN/m Spring [25]

8.4.2.3 User Experience Feedback

Each caravan was driven around the same route as detailed above by an experienced caravan user. The driver was asked to provide feedback on the driving experience during each test.

Original Alko Caravan

- Less body motion noticed in the rear view mirror (pitch and roll)
- The caravan felt ‘heavier’
- On acceleration the steering felt lighter despite the nose weights being matched
- The ride felt a lot harsher to the driver generating a ‘sea sick’ sensation
- The caravan transmitted more vibrations to the car
- The caravan felt less stable

Prototype

- More body motion noticed in rear view mirror (disconcerting to driver)
- The caravan felt a lot smoother to tow
- Less vibration transmitted to the car and driver
- Noticed the caravan a lot less when towing

8.5 Conclusion

These results provide a good first indication that the prototype suspension system is a very significant improvement upon the current ALKO based suspension used on current Bailey caravans. Not only is the suspension of a lower stiffness and higher damping, it also has a longer stroke in bump and rebound that enhances the vibration isolation characteristics of the caravan suspension. It is also encouraging that the user feedback indicates that the new system would result in a more positive towing experience, something that was overlooked at the inception of the project. Further investigation needs to be conducted to investigate the dynamic stability of the caravan including 'snaking' speeds compared with the Alko system. It is anticipated that a softer suspension system may lead to lower snaking speeds. It is important that the inertia of the caravan is equal to that of a full production caravan. This means that a third 'pre-production' prototype should be built with a fully specified caravan interior. Following this, the prototype should undergo accelerated life tests to draw a firm conclusion on whether it is a viable replacement for the Alko system.

This product development process has indicated that there is a viable alternative design for caravan chassis and suspension that could be introduced to the majority of caravan manufacturers throughout the UK. The new design incorporates an optimised suspension system, a lighter structure (40kg lighter than the Alko equivalent), enhanced weather proofing capabilities and retains overall structural stiffness. The system could bring numerous benefits to the end user but primarily it will reduce the demand on the tow vehicle meaning that a smaller car could tow the same specification caravan that was previously too heavy.

It has been concluded that, following further testing, there is the potential for the system to be developed into a mass produced product. The following final chapter summarises the commercial prospects of the system, should it be taken to mass production.

9 : Further Work and Commercialisation

9.1 Further Work

9.1.1 Stability Testing

The author did not have time to compete a satisfactory investigation into the stability of the new chassis and suspension system when on tow. It is therefore suggested that this should be carried out prior to progressing to mass production.

The most common manifestation of instability in caravans is known as snaking where, usually at high speeds, the caravan begins to oscillate dangerously about the tow hitch. Research by Killer [26] has suggested several solutions to prevent snaking from taking place and the caravan market has seen the introduction of several anti-snaking third party devices such as the Alko ATC system. Although caravan snaking has improved in recent years the phenomenon is widely regarded as the most common cause of caravan accidents and it is important that the road handling performance of any new chassis and suspension design should be investigated thoroughly. It is suggested that the new design should be subjected to the same testing as outlined in [26]. This will allow the results to be compared to a benchmark set of data that is deemed an industry norm and safe to use on public roads.

9.1.2 Accelerated Life Testing

The best way to measure whether the new system has truly improved the design of a caravan chassis is to repeat the accelerated life test conducted at the beginning of this project. It was shown that the Alko system survived approximately 47% of the ‘car-based’ test although subsequent testing indicated that this could be as low as 23%. It is recommended that a repeat of the same test with a third full spec caravan prototype should be conducted and the results compared to the Alko chassis test data. An improvement on 50% would indicate that not only is the new chassis/suspension design lighter and more compliant but also is stronger and more robust than the Alko system.

9.2 Commercialisation

There is great potential to develop the new chassis system into a viable profit-making venture. The following section summarises a brief investigation into the best way of bringing the new design to market with a focus on developing the product with Bailey Caravans.

9.2.1 Review of the Current Market

In 2011 it is estimated that 22,000 touring caravans were manufactured in the UK [27]. As the biggest British manufacturer, Bailey contributed 7,500 (33%) to this total, a figure which, although slightly down from 2009, has been consistently high over the past five years. In Europe, around 81,000 leisure vehicles were manufactured (including the figure from the UK) with Germany having the biggest contribution having made 35,000 units [27].

In general, market sales are down from previous years primarily due to the turbulent economy in the EU and the hangover from the 2008 recession. Nevertheless the market grew in the years leading up to this period and is set to bloom once more as camping and caravanning becomes more popular, particularly amongst young families. Growth in the Australian market is particularly strong and Bailey has begun exporting to Melbourne to capitalise on the strength of the Australian Dollar against the UK Pound.

Alko supply caravan chassis to over 80% of the caravan manufacturers in the European Union and in 2010 generated a turnover of £28m in the UK alone [28]. Other products in the Alko portfolio include motor home chassis and gardening equipment. They also have a strong market presence in the USA and Australia. Presently Bailey spends around £8m a year on Alko products meaning 30% of Alko's revenue is attributed to Bailey Caravan sales alone.

9.2.2 Opportunity

The new chassis design presents Bailey with the opportunity to develop a product that is lightweight, weather proof and exhibits better dynamic performance than the Alko system. The development of such a product will also dramatically reduce the reliance on a monopoly supplier and will give greater creative control to Bailey. In order for the product to be commercially attractive it is important that it matches or is lower than the cost of the equivalent Alko product. It should also be considered that such a system would be appealing to other UK caravan manufacturers and that presenting the system as a rival to Alko could be extremely profitable.

9.2.3 Proposed Commercial Model

Following a review of several commercial models, it was concluded that the most appropriate would be to set up a spin off manufacturing business that would develop the system under a different brand name. It was also concluded that in order to gain market confidence, Bailey should form a partnership with an existing reputable trailer or chassis manufacturer.

The chosen partner would undoubtedly require substantial evidence that proved that the new system is commercially viable as an alternative to the current product. If the product shows potential it would offer the chance to segment the market offering the product as a high end, high spec, and high value option. Developing in partnership with an existing strong brand would place the product in a good position without heavily investing into a whole new marketing strategy. A joint venture would ensure robust product development and strong backing from an established chassis manufacturer.

Regardless of the partnership arrangements a new production facility will have to be developed to manufacture the product. If the product is made adjacent to the Bailey factory it will inevitably be linked with the Bailey brand and other caravan manufacturers are less likely to adopt a competitors product. Further investigation would have to be conducted into the optimum location for the production facility.

A return on investment into the manufacturing facilities will be generated from cost savings (compared to buying the Alko product) and eventual sales to other caravan manufacturers.

The setup of a spin-off company could facilitate the development of other devices such as hitch couplers and brake systems.

In keeping with the current manufacturing system, the product will be delivered to the Bailey factory and other manufacturers based on a just-in time requirement.

9.2.4 Marketability

The partnership with an existing strong brand manufacturer will make this product extremely marketable to a large proportion of the European caravan market. The product could initially be targeted at the higher end models then developed to suit the other market segments for maximum market penetration. It is anticipated that Bailey would receive market exclusivity for a period of time to gain first mover advantage over the competition. This would cap the initial revenue but would help to validate the product in the marketplace before a full-scale commercial release. Significant investment from both Baileys and the partner collaborator would be required but the potential returns are very high. A prima facie financial forecast is provided in Appendix V.

10 : CONCLUSIONS

10.1 Project Objectives Summary

The aim of this project was to investigate the performance of the current state-of-the-art caravan design with specific focus on the chassis and suspension system. The investigation comprised of detailed structural analysis of the present Alko chassis system through both simulated models and real-life track based testing. The suspension performance was investigated through laboratory based tests, in-house experimentation and road tests.

Following this investigation the design of the sub-structure was reviewed and an alternative caravan chassis and suspension system were developed. The intention was to design and develop an alternative system that was significantly lighter, as equally robust and cost effective as the incumbent design. It was specified that an overall weight saving of 50kg (or 12% of the chassis weight) should be achieved.

The other key objective of the project was to ensure that the final design could be easily adapted into a mass-produced system, capable of matching the current demand for chassis and suspension systems based on Bailey Caravans' current manufacturing figures, approximately 8,000 caravans per annum.

10.2 Project Findings

The investigation found that the suspension stiffness on present caravans is approximately four times stiffer than that of a car of the same mass. In extreme circumstances, such as travelling through a deep pothole or over a sleeping policeman at speeds above 15mph, this high stiffness characteristic resulted in a force being transmitted to the chassis that was large enough to induce crack propagation, ultimately leading to component failure. Under normal road conditions the suspension system provided little to no damping resulting in a significant vibration of approximately 2Hz being transmitted to the body and interior of the caravan. It was found that in some case this caused damage to internal furniture and caused items to fall out from cupboards. It was concluded that the stiffness and strength of the present chassis and floor design was adequate under normal static loads although the weight could be reduced.

This investigation indicated that there was potential to reduce the stiffness of the suspension system and reduce the weight of the chassis whilst maintaining the structural stiffness and strength properties.

The challenge lent itself well to the use of composite materials but it was important to be mindful of the fact that the system should remain to be the same cost to manufacture as the present design. An investigation into suitable materials concluded that a sandwich panel structure comprising of an aluminium skin and a high-density foam core offered the best solution in terms of strength, weight and cost effectiveness. The panels were configured into a three dimensional 'floor and spine' structure based on a simple optimisation analysis.

Several suspension systems were reviewed and it was concluded that a trailing arm and damped coil spring configuration resulted in a system that was inexpensive to manufacture, easier to maintain, easier to optimise and slightly lighter than the incumbent system. The suspension was designed to provide increased damping at the normal ride frequency (approximately 1.5-2Hz). The suspension system also had larger overall travel compared to the present system that ensured that bump stops would only engage in extreme road conditions.

The chassis and suspension systems were designed and developed in parallel and three prototypes were successfully built. The first prototype was approximately 10kg lighter (chassis plus suspension) than the Alko equivalent but was twice as stiff when statically loaded. Prototype one's suspension system was configured as a 'coil over damper' which proved extremely hard to install and had limited travel but did exhibit better ride characteristics than the Alko system.

The second prototype chassis had significantly reduced bulk that resulted in a lighter structure of approximately the same stiffness as the Alko system. Prototype two's suspension has a separated coil and spring allowing for easier installation, easier maintenance and far greater travel. The ride analysis showed that that the system reduced internal vibration transmission by over a factor of ten. The total mass (chassis plus suspension) was approximately 45kg less than the equivalent Alko system.

The third prototype was identical to the second but had a fully specified caravan body and interior. The testing for the system is on going and has shown positive results to date. Independent test drivers have stated that the new system offers a substantially improved towing experience to the driver and is easier to tow than the traditional system. It is the intention of Bailey Caravans to develop this system as an independent commercial entity and potentially market it to other caravan manufacturers.

10.3 Final Conclusions

The project has indicated that there is strong potential to develop a lightweight, robust chassis system capable of matching a caravan's ride quality closer to that of the tow vehicle. The system maintains simple manufacturing methods, has enhanced weather-proofing characteristics and is scalable to a wide variety of caravan sizes. Moreover, the new system can be manufactured at a cost which is comparable with the present design although will initially require significant capital investment.

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APPENDICES

APPENDIX I: THE ALU-TECH CONSTRUCTION METHOD

The Alu-Tech construction system is the first of its kind in the UK caravan industry and shares many similarities with the monocoque production designs currently used in the automotive industry.

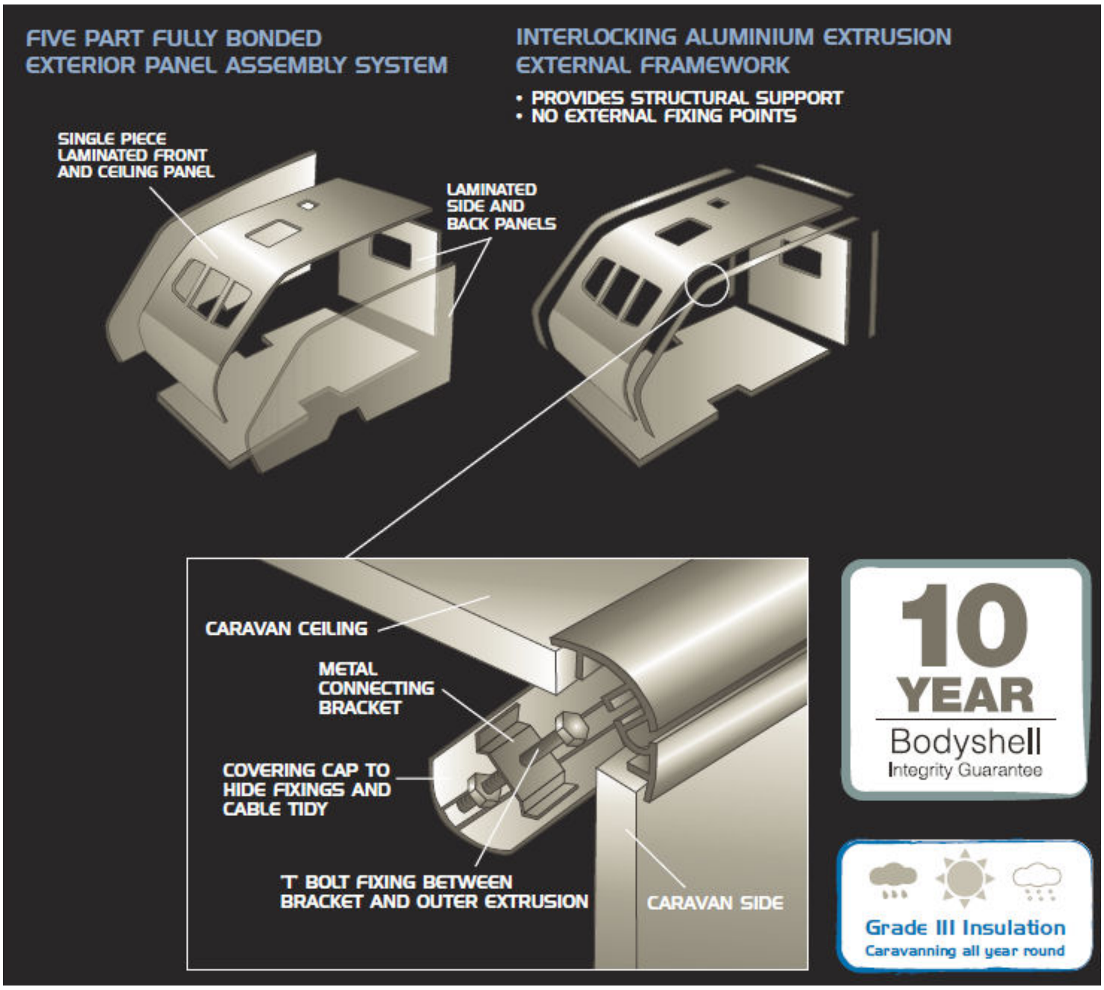
It incorporates a system whereby the individual body shell components all contribute to the overall strength of the structure rather than solely relying on the floor and chassis.
The assembly consists of a five part, as opposed to the current nine part, system and comprises of a traditional caravan floor, two laminated side panels, a solid laminated back panel and a new single span front and roof section.

The body shell panels are then clamped together with a bespoke aluminium extrusion framework that provides additional structural rigidity.

In addition to the extra strength this system provides the other main benefit of this new design is the absence of any external fixings that has a major impact on reducing the opportunity for water ingress into the body shell.
The outer aluminium extrusion houses the body shell panels and they are then held in place from the inside by a metal connecting bracket. The whole assembly is then locked together by a T-bolt fixing whilst a semi-circular plastic cap covers the fittings to give a neat interior finish.

To combat the problem of water ingress Bailey has introduced not one but two lines of defence into the Alu-Tech body shell design.
The first line of defence is ingress prevention, where by every conceivable effort has been made to reduce the number of potential water access points, with a 90% reduction in the number of external joints and fixing points, thus improving the overall integrity of the protective shell.

The second line of defence is ingress management, minimising the impact any possible ingress may cause. This has been achieved with the development of timber free body shell panels, featuring composite plastic internal skeleton, low absorbency buffer zones surrounding the windows and doors.



Appendix II: D85C Proving Test

CYCLE	No. OF CYCLES IN B3 (GVW) LOAD CONDITION	DISTANCE (miles)	TOTAL TEST DISTANCE (miles)
PAVE @ 10mph	231	0.9	207.9
30° KERB STRIKE @ 5mph	63	0.5	31.5
HILL ROUTE	30	2.1	63.0
TWIST HUMPS @ 10mph	99	1.2	118.8
HIGH SPEED	51	4.2	214.2
HANDLING CIRCUIT WITH POTHOLES	24	0.9	21.6
		TOTAL DISTANCE	657.0

Appendix III: Bailey Plant

Main Factory – Trim Line, Bulkhead, Floor, Axel, Beds, Furniture Assembly and Tbarbing.

West Works – Upstairs - Bed Frames, draw assembly, plastics cutting, bathroom door.

Downstairs – Frame assembly, ply pressing, furniture CNC and sanding.

Reception and Head Office –Sales and after sales, marketing, front of house/meeting rooms.

East Works – Sides and ceilings, side windows and vent doors.

Storage – bought in parts, work tops, preformed plastic parts, axel parts etc.

Waste handling, recycling and timber collection.

VIPs, commissioning, repairs.

Delivery point, waste collection.

Dispatch

Appendix IV: FEA Mesh Details

Mesh Details for Original Floor

Mesh Details

Study name	Study 1 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Curvature based mesh
Jacobian points	4 points
Mesh Control	Defined
Max Element Size	171.923 mm
Min Element Size	34.3845 mm
Mesh quality	High
Total nodes	43308
Total elements	19779
Maximum Aspect Ratio	717.9
Percentage of elements with Aspect Ratio < 3	0.435
Percentage of elements with Aspect Ratio > 10	78.8
% of distorted elements (Jacobian)	0
Remesh failed parts with incompatible mesh	Off
Time to complete mesh(hh:mm:ss)	00:00:08
Computer name	JACK-PC

Mesh Details for Prototype

Mesh Details

Study name	Study 1 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Curvature based mesh
Jacobian points	4 points
Max Element Size	211.892 mm
Min Element Size	42.3784 mm
Mesh quality	High
Total nodes	32705
Total elements	14582
Maximum Aspect Ratio	603.52
Percentage of elements with Aspect Ratio < 3	2.25
Percentage of elements with Aspect Ratio > 10	71.3
% of distorted elements (Jacobian)	0
Remesh failed parts with incompatible mesh	Off
Time to complete mesh(hh:mm:ss)	00:00:09
Computer name	JACK-PC

APPENDIX V: FINANCIAL FORECAST

Profit and Loss Forecast for Commercial Model Three: Costs and profit attributed to Bailey based on a 50:50 investment

Years 1-2 operating in UK market. Years 2 onwards operating in European Market.

Total capital investment required is (over 6 years) £3m

Cost to Bailey			**Total Cost**			
Technicom	£ 73,500		**Technicom**	£ 147,000		
Laser	£ 12,500		**Laser**	£ 25,000		
Decoiler	£ 7,500		**Decoiler**	£ 15,000		
Maka	£ 182,500		**Maka**	£ 365,000		
Press	£ 129,000		**Press**	£ 258,000		
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**
Sales (Complete Systems)	4,000	8,000	12,000	16,000	20,000	20,000
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**
Capital Investment						
Technicom	£ 24,500	£ 24,500	£ 24,500	£ 24,500	£ 49,000	
Laser	£ 4,167	£ 4,167	£ 4,167	£ 4,167	£ 8,333	
Decoiler	£ 2,500	£ 2,500	£ 2,500	£ 2,500	£ 5,000	
Maka	£ 60,833	£ 60,833	£ 60,833	£ 60,833	£ 121,667	
Press	£ 43,000	£ 43,000	£ 43,000	£ 43,000	£ 86,000	
Factory Renovation+ Rent	£ 100,000	£ 60,000	£ 66,000	£ 72,600	£ 79,860	£ 87,846
Tools and Other Equipment	£ 20,000	£ 10,000	£ 10,000	£ 10,000	£ 10,000	£ 10,000
IT Systems	£ 40,000			£ 40,000		
Fixed Costs						
Utilities	£ 8,000	£ 12,000	£ 18,000	£ 27,000	£ 40,500	£ 60,750
Insurance	£ 10,000	£ 10,000	£ 10,000	£ 10,000	£ 10,000	£ 10,000
Storage	£ 5,000	£ 7,500	£ 11,250	£ 16,875	£ 25,313	£ 37,969
Staff	£ 200,000	£ 280,000	£ 392,000	£ 548,800	£ 768,320	£ 845,152
Variable Costs						
Raw Materials	£ 1,700,000	£ 3,400,000	£ 5,100,000	£ 6,800,000	£ 8,500,000	£ 8,500,000
Shipping	£ 50,000	£ 60,000	£ 72,000	£ 86,400	£ 103,680	£ 124,416
R&D		£ 20,000	£ 26,000	£ 33,800	£ 43,940	£ 57,122
Maintenance	£ 10,000	£ 12,000	£ 14,400	£ 17,280	£ 20,736	£ 24,883
Total Costs	**£ 2,278,000**	**£ 4,006,500**	**£ 5,854,650**	**£ 7,797,755**	**£ 9,872,349**	**£ 9,758,138**
Sales	**£ 2,266,667**	**£ 4,533,333**	**£ 6,800,000**	**£ 9,066,667**	**£ 11,333,333**	**£ 11,333,333**
Profit	**-£ 11,333**	**£ 526,833**	**£ 945,350**	**£ 1,268,912**	**£ 1,460,985**	**£ 1,575,195**
Present Value	**-£ 11,333**	**£ 477,853**	**£ 816,629**	**£ 1,043,937**	**£ 1,144,720**	**£ 1,234,207**
Total Investment	**£ 1,426,306**					
NPV	**£ 3,471,806**					
IRR Approx	**1.5 Years**					

These figures do not account for the saving derived from 'self-manufacture', i.e. the savings associated with no longer buying the current Alko system. If considered this will reduce discounted costs by a further £2.4m resulting in a total NPV **of £5.9m over 6 years**.

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